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# Aviation and the Global Atmosphere: A Special Report of IPCC Working Groups I and III

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This excerpt from the IPCC publication,*Aviation and the Global Atmosphere*, includes the summary for policymakers and Chapter 9 "Aircraft Emissions: Current Inventories and Future Scenarios."
The complete report is available on the web at http://www.ipcc.ch
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# Aviation and the Global Atmosphere: A Special Report of IPCC Working Groups I and III

**Abstract**

This report assesses the effects of aircraft on climate and atmospheric ozone and is the first IPCC report for a specific industrial subsector. It was prepared by IPCC in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, in response to a request by the International Civil Aviation Organization (ICAO) because of the potential impact of aviation emissions. These are the predominant anthropogenic emissions deposited directly into the upper troposphere and lower stratosphere.

Aviation has experienced rapid expansion as the world economy has grown. Passenger traffic (expressed as revenue passenger kilometers) has grown since 1960 at nearly 9% per year, 2.4 times the average Gross Domestic Product (GDP) growth rate. Freight traffic, approximately 80% of which is carried by passenger airplanes, has also grown over the same time period. The rate of growth of passenger traffic has slowed to about 5% in 1997 as the industry is maturing. Total aviation emissions have increased, because increased demand for air transport has outpaced the reductions in specific emissions from the continuing improvements in technology and operational procedures. Passenger traffic, assuming unconstrained demand, is projected to grow at rates in excess of GDP for the period assessed in this report.

**Keywords**

global warming, aircraft, emissions, chemistry

**Comments**

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# SUMMARY FOR POLICYMAKERS

# AVIATION AND THE GLOBAL ATMOSPHERE

***A Special Report of Working Groups I and III of the Intergovernmental Panel on Climate Change***

*This summary, approved in detail at a joint session of IPCC Working Groups I and III (San José, Costa Rica • 12-14 April 1999), represents the formally agreed statement of the IPCC concerning current understanding of aviation and the global atmosphere.*

Based on a draft prepared by:

*David H. Lister, Joyce E. Penner, David J. Griggs, John T. Houghton, Daniel L. Albritton, John Begin, Gerard Bekebrede, John Crayston, Ogunlade Davidson, Richard G. Derwent, David J. Dokken, Julie Ellis, David W. Fahey, John E. Frederick, Randall Friedl, Neil Harris, Stephen C. Henderson, John F. Hennigan, Ivar Isaksen, Charles H. Jackman, Jerry Lewis, Mack McFarland, Bert Metz, John Montgomery, Richard W. Niedzwiecki, Michael Prather, Keith R. Ryan, Nelson Sabogal, Robert Sausen, Ulrich Schumann, Hugh J. Somerville, N. Sundararaman, Ding Yihui, Upali K. Wickrama, Howard L. Wesoky*

## 1. Introduction

*This report assesses the effects of aircraft on climate and atmospheric ozone and is the first IPCC report for a specific industrial subsector. It was prepared by IPCC in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, in response to a request by the International Civil Aviation Organization (ICAO)[1] because of the potential impact of aviation emissions. These are the predominant anthropogenic emissions deposited directly into the upper troposphere and lower stratosphere.*

*Aviation has experienced rapid expansion as the world economy has grown. Passenger traffic (expressed as revenue passenger-kilometers[2]) has grown since 1960 at nearly 9% per year, 2.4 times the average Gross Domestic Product (GDP) growth rate. Freight traffic, approximately 80% of which is carried by passenger airplanes, has also grown over the same time period. The rate of growth of passenger traffic has slowed to about 5% in 1997 as the industry is maturing.* Total aviation emissions have increased, because increased demand for air transport has outpaced the reductions in specific emissions[3] from the continuing improvements in technology and operational procedures. Passenger traffic, assuming unconstrained demand, is projected to grow at rates in excess of GDP for the period assessed in this report.

The effects of current aviation and of a range of unconstrained growth projections for aviation (which include passenger, freight, and military) are examined in this report, including the possible effects of a fleet of second generation, commercial supersonic aircraft. The report also describes current aircraft technology, operating procedures, and options for mitigating aviation's future impact on the global atmosphere. The report does not consider the local environmental effects of aircraft engine emissions or any of the indirect environmental effects of aviation operations such as energy usage by ground transportation at airports.

## 2. How Do Aircraft Affect Climate and Ozone?

*Aircraft emit gases and particles directly into the upper troposphere and lower stratosphere where they have an impact on atmospheric composition. These gases and particles alter the concentration of atmospheric greenhouse gases, including carbon dioxide ($CO_2$), ozone ($O_3$), and methane ($CH_4$); trigger formation of condensation trails (contrails); and may increase cirrus cloudiness—all of which contribute to climate change (see Box 1).*

The principal emissions of aircraft include the greenhouse gases carbon dioxide and water vapor ($H_2O$). Other major emissions are nitric oxide (NO) and nitrogen dioxide ($NO_2$) (which together are termed $NO_x$), sulfur oxides ($SO_x$), and soot. The total amount of aviation fuel burned, as well as the total emissions of carbon dioxide, $NO_x$, and water vapor by aircraft, are well known relative to other parameters important to this assessment.

The climate impacts of the gases and particles emitted and formed as a result of aviation are more difficult to quantify than the emissions; however, they can be compared to each other and to climate effects from other sectors by using the concept of radiative forcing.[4] Because carbon dioxide has a long atmospheric residence time (≈100 years) and so becomes well mixed throughout the atmosphere, the effects of its emissions from aircraft are indistinguishable from the same quantity of carbon dioxide emitted by any other source. The other gases (e.g., $NO_x$, $SO_x$, water vapor) and particles have shorter atmospheric residence times and remain concentrated near flight routes, mainly in the northern mid-latitudes. These emissions can lead to radiative forcing that is regionally located near the flight routes for some components (e.g., ozone and contrails) in contrast to emissions that are globally mixed (e.g., carbon dioxide and methane).

The global mean climate change is reasonably well represented by the global average radiative forcing, for example, when evaluating the contributions of aviation to the rise in globally averaged temperature or sea level. However, because some of aviation's key contributions to radiative forcing are located mainly in the northern mid-latitudes, the regional climate response may differ from that derived from a global mean radiative forcing. The impact of aircraft on regional climate could be important, but has not been assessed in this report.

Ozone is a greenhouse gas. It also shields the surface of the earth from harmful ultraviolet (UV) radiation, and is a common air pollutant. Aircraft-emitted $NO_x$ participates in ozone chemistry. Subsonic aircraft fly in the upper troposphere and lower stratosphere (at altitudes of about 9 to 13 km), whereas supersonic aircraft cruise several kilometers higher (at about 17 to 20 km) in the stratosphere. Ozone in the upper troposphere and lower stratosphere is expected to increase in response to $NO_x$ increases and methane is expected to decrease. At higher altitudes, increases in $NO_x$ lead to decreases in the stratospheric ozone layer. Ozone precursor ($NO_x$) residence times in these regions increase with altitude, and hence perturbations to ozone by aircraft depend on the altitude of $NO_x$ injection and vary from regional in scale in the troposphere to global in scale in the stratosphere.

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[1] ICAO is the United Nations specialized agency that has global responsibility for the establishment of standards, recommended practices, and guidance on various aspects of international civil aviation, including environmental protection.

[2] The revenue passenger-km is a measure of the traffic carried by commercial aviation: one revenue-paying passenger carried 1 km.

[3] Specific emissions are emissions per unit of traffic carried, for instance, per revenue passenger-km.

[4] Radiative forcing is a measure of the importance of a potential climate change mechanism. It expresses the perturbation or change to the energy balance of the Earth-atmosphere system in watts per square meter ($Wm^{-2}$). Positive values of radiative forcing imply a net warming, while negative values imply cooling.

***Table 1**: Summary of future global aircraft scenarios used in this report.*

| Scenario Name | Avg. Traffic Growth per Year (1990–2050)[1] | Avg. Annual Growth Rate of Fuel Burn (1990–2050)[2] | Avg. Annual Economic Growth Rate | Avg. Annual Population Growth Rate | Ratio of Traffic (2050/1990) | Ratio of Fuel Burn (2050/1990) | Notes |
|---|---|---|---|---|---|---|---|
| Fa1 | 3.1% | 1.7% | 2.9% *1990–2025* 2.3% *1990–2100* | 1.4% *1990–2025* 0.7% *1990–2100* | 6.4 | 2.7 | Reference scenario developed by ICAO Forecasting and Economic Support Group (FESG); mid-range economic growth from IPCC (1992); technology for both improved fuel efficiency and $NO_x$ reduction |
| Fa1H | 3.1% | 2.0% | 2.9% *1990–2025* 2.3% *1990–2100* | 1.4% *1990–2025* 0.7% *1990–2100* | 6.4 | 3.3 | Fa1 traffic and technology scenario with a fleet of supersonic aircraft replacing some of the subsonic fleet |
| Fa2 | 3.1% | 1.7% | 2.9% *1990–2025* 2.3% *1990–2100* | 1.4% *1990–2025* 0.7% *1990–2100* | 6.4 | 2.7 | Fa1 traffic scenario; technology with greater emphasis on $NO_x$ reduction, but slightly smaller fuel efficiency improvement |
| Fc1 | 2.2% | 0.8% | 2.0% *1990–2025* 1.2% *1990–2100* | 1.1% *1990–2025* 0.2% *1990–2100* | 3.6 | 1.6 | FESG low-growth scenario; technology as for Fa1 scenario |
| Fe1 | 3.9% | 2.5% | 3.5% *1990–2025* 3.0% *1990–2100* | 1.4% *1990–2025* 0.7% *1990–2100* | 10.1 | 4.4 | FESG high-growth scenario; technology as for Fa1 scenario |
| Eab | 4.0% | 3.2% | | | 10.7 | 6.6 | Traffic-growth scenario based on IS92a developed by Environmental Defense Fund (EDF); technology for very low $NO_x$ assumed |
| Edh | 4.7% | 3.8% | | | 15.5 | 9.4 | High traffic-growth EDF scenario; technology for very low $NO_x$ assumed |

[1]Traffic measured in terms of revenue passenger-km.
[2]All aviation (passenger, freight, and military).

ideal air traffic management) is achieved by 2050. If these improvements do not materialize then fuel use and emissions will be higher. It is further assumed that the number of aircraft as well as the number of airports and associated infrastructure will continue to grow and not limit the growth in demand for air travel. If the infrastructure was not available, the growth of traffic reflected in these scenarios would not materialize.

IPCC (1992)[7] developed a range of scenarios, IS92a-f, of future greenhouse gas and aerosol precursor emissions based on assumptions concerning population and economic growth, land use, technological changes, energy availability, and fuel mix during the period 1990 to 2100. Scenario IS92a is a mid-range emissions scenario. Scenarios of future emissions are not predictions of the future. They are inherently uncertain because they are based on different assumptions about the future, and

[7] **IPCC,** 1992: *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* [Houghton, J.T., B.A. Callander, and S.K.Varney (eds.)]. Cambridge University Press, Cambridge, UK, 200 pp.

the longer the time horizon the more uncertain these scenarios become. The aircraft emissions scenarios developed here used the economic growth and population assumptions found in the IS92 scenario range (see Table 1 and Figure 1). In the following sections, scenario Fa1 is utilized to illustrate the possible effects of aircraft and is called the reference scenario. Its assumptions are linked to those of IS92a. The other aircraft emissions scenarios were built from a range of economic and population projections from IS92a-e. These scenarios represent a range of plausible growth for aviation and provide a basis for sensitivity analysis for climate modeling. However, the high growth scenario Edh is believed to be less plausible and the low growth scenario Fc1 is likely to be exceeded given the present state of the industry and planned developments.

## 4. What are the Current and Future Impacts of Subsonic Aviation on Radiative Forcing and UV Radiation?

The summary of radiative effects resulting from aircraft engine emissions is given in Figures 2 and 3. As shown in Figure 2, the uncertainty associated with several of these effects is large.

### *4.1. Carbon Dioxide*

*Emissions of carbon dioxide by aircraft were 0.14 Gt C/year in 1992. This is about 2% of total anthropogenic carbon dioxide emissions in 1992 or about 13% of carbon dioxide emissions from all transportation sources. The range of scenarios considered here projects that aircraft emissions of carbon dioxide will continue to grow and by 2050 will be 0.23 to 1.45 Gt C/year. For the reference scenario (Fa1) this emission increases 3-fold*

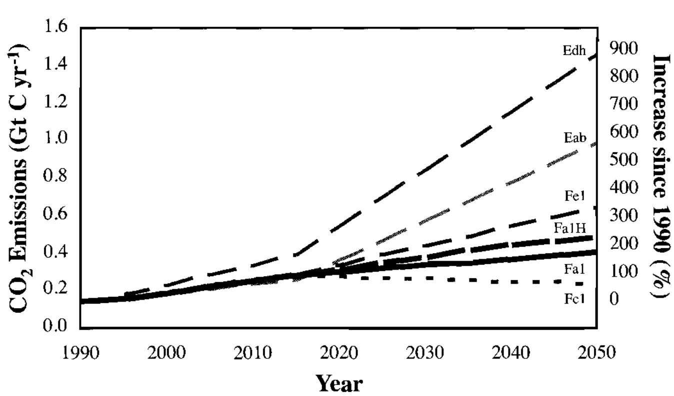


**Figure 1**: Total aviation carbon dioxide emissions resulting from six different scenarios for aircraft fuel use. Emissions are given in Gt C [or billion ($10^9$) tonnes of carbon] per year. To convert Gt C to Gt $CO_2$ multiply by 3.67. The scale on the righthand axis represents the percentage growth from 1990 to 2050. Aircraft emissions of carbon dioxide represent 2.4% of total fossil fuel emissions of carbon dioxide in 1992 or 2% of total anthropogenic carbon dioxide emissions. (Note: Fa2 has not been drawn because the difference from scenario Fa1 would not be discernible on the figure.)

*by 2050 to 0.40 Gt C/year, or 3% of the projected total anthropogenic carbon dioxide emissions relative to the mid-range IPCC emission scenario (IS92a). For the range of scenarios, the range of increase in carbon dioxide emissions to 2050 would be 1.6 to 10 times the value in 1992.*

Concentrations of and radiative forcing from carbon dioxide today are those resulting from emissions during the last 100 years or so. The carbon dioxide concentration attributable to aviation in the 1992 atmosphere is 1 ppmv, a little more than 1% of the total anthropogenic increase. This percentage is lower than the percentage for emissions (2%) because the emissions occurred only in the last 50 years. For the range of scenarios in Figure 1, the accumulation of atmospheric carbon dioxide due to aircraft over the next 50 years is projected to increase to 5 to 13 ppmv. For the reference scenario (Fa1) this is 4% of that from all human activities assuming the mid-range IPCC scenario (IS92a).

### *4.2. Ozone*

*The $NO_x$ emissions from subsonic aircraft in 1992 are estimated to have increased ozone concentrations at cruise altitudes in northern mid-latitudes by up to 6%, compared to an atmosphere without aircraft emissions. This ozone increase is projected to rise to about 13% by 2050 in the reference scenario (Fa1).* The impact on ozone concentrations in other regions of the world is substantially less. These increases will, on average, tend to warm the surface of the Earth.

Aircraft emissions of $NO_x$ are more effective at producing ozone in the upper troposphere than an equivalent amount of emission at the surface. Also increases in ozone in the upper troposphere are more effective at increasing radiative forcing than increases at lower altitudes. Due to these increases the calculated total ozone column in northern mid-latitudes is projected to grow by approximately 0.4 and 1.2% in 1992 and 2050, respectively. However, aircraft sulfur and water emissions in the stratosphere tend to deplete ozone, partially offsetting the $NO_x$-induced ozone increases. The degree to which this occurs is, as yet, not quantified. Therefore, the impact of subsonic aircraft emissions on stratospheric ozone requires further evaluation. The largest increases in ozone concentration due to aircraft emissions are calculated to occur near the tropopause where natural variability is high. Such changes are not apparent from observations at this time.

### *4.3. Methane*

*In addition to increasing tropospheric ozone concentrations, aircraft $NO_x$ emissions are expected to decrease the concentration of methane, which is also a greenhouse gas. These reductions in methane tend to cool the surface of the Earth. The methane concentration in 1992 is estimated here to be about 2% less than that in an atmosphere without aircraft.* This aircraft-induced reduction of methane concentration is much smaller than the observed overall 2.5-fold increase since pre-industrial times. Uncertainties in the sources and sinks of methane preclude testing the impact of aviation on methane concentrations with atmospheric observations. *In the reference scenario (Fa1) methane would be about 5% less than that calculated for a 2050 atmosphere without aircraft.*

Changes in tropospheric ozone are mainly in the Northern Hemisphere, while those of methane are global in extent so that, even though the global average radiative forcings are of similar magnitude and opposite in sign, the latitudinal structure of the forcing is different so that the net regional radiative effects do not cancel.

### 4.4. Water Vapor

*Most subsonic aircraft water vapor emissions are released in the troposphere where they are rapidly removed by precipitation within 1 to 2 weeks. A smaller fraction of water vapor emissions is released in the lower stratosphere where it can build up to larger concentrations. Because water vapor is a greenhouse gas, these increases tend to warm the Earth's surface, though for subsonic aircraft this effect is smaller than those of other aircraft emissions such as carbon dioxide and $NO_x$.*

### 4.5. Contrails

*In 1992, aircraft line-shaped contrails are estimated to cover about 0.1% of the Earth's surface on an annually averaged basis with larger regional values. Contrails tend to warm the Earth's surface, similar to thin high clouds. The contrail cover is projected to grow to 0.5% by 2050 in the reference scenario (Fa1), at a rate which is faster than the rate of growth in aviation fuel consumption.* This faster growth in contrail cover is expected because air traffic will increase mainly in the upper troposphere where contrails form preferentially, and may also occur as a result of improvements in aircraft fuel efficiency. Contrails are triggered from the water vapor emitted by aircraft and their optical properties depend on the particles emitted or formed in the aircraft plume and on the ambient atmospheric conditions. The radiative effect of contrails depends on their optical properties and global cover, both of which are uncertain. Contrails have been observed as line-shaped clouds by satellites

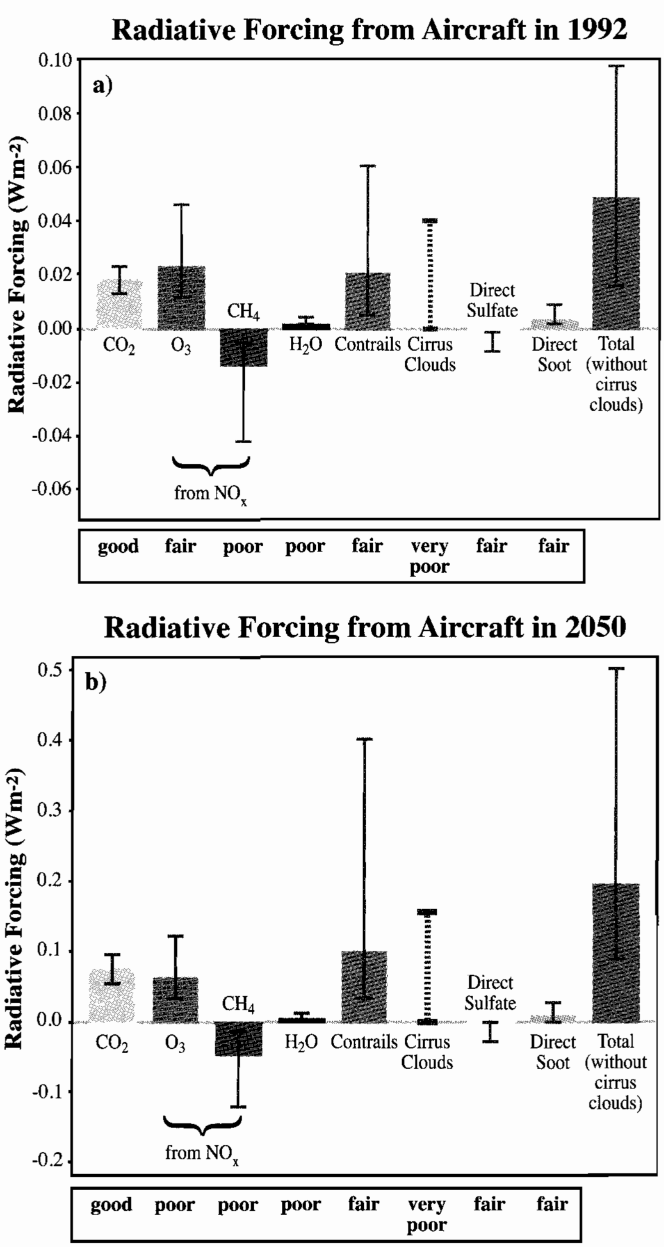


**Figure 2**: Estimates of the globally and annually averaged radiative forcing ($Wm^{-2}$) (see Footnote 4) from subsonic aircraft emissions in 1992 (*2a*) and in 2050 for scenario Fa1 (*2b*). The scale in Figure 2b is greater than the scale in 2a by about a factor of 4. The bars indicate the best estimate of forcing while the line associated with each bar is a two-thirds uncertainty range developed using the best knowledge and tools available at the present time. (The two-thirds uncertainty range means that there is a 67% probability that the true value falls within this range.) The available information on cirrus clouds is insufficient to determine either a best estimate or an uncertainty range; the dashed line indicates a range of possible best estimates. The estimate for total forcing does not include the effect of changes in cirrus cloudiness. The uncertainty estimate for the total radiative forcing (without additional cirrus) is calculated as the square root of the sums of the squares of the upper and lower ranges for the individual components. The evaluations below the graph ("good," "fair," "poor," "very poor") are a relative appraisal associated with each component and indicates the level of scientific understanding. It is based on the amount of evidence available to support the best estimate and its uncertainty, the degree of consensus in the scientific literature, and the scope of the analysis. This evaluation is separate from the evaluation of uncertainty range represented by the lines associated with each bar. This method of presentation is different and more meaningful than the confidence level presented in similar graphs from *Climate Change 1995: The Science of Climate Change*.

over heavy air traffic areas and covered on average about 0.5% of the area over Central Europe in 1996 and 1997.

### 4.6. Cirrus Clouds

*Extensive cirrus clouds have been observed to develop after the formation of persistent contrails. Increases in cirrus cloud cover (beyond those identified as line-shaped contrails) are found to be positively correlated with aircraft emissions in a limited number of studies.* About 30% of the Earth is covered with cirrus cloud. *On average an increase in cirrus cloud cover tends to warm the surface of the Earth. An estimate for aircraft-induced cirrus cover for the late 1990s ranges from 0 to 0.2% of the surface of the Earth. For the Fa1 scenario, this may possibly increase by a factor of 4 (0 to 0.8%) by 2050;* however, the mechanisms associated with increases in cirrus cover are not well understood and need further investigation.

### 4.7. Sulfate and Soot Aerosols

*The aerosol mass concentrations in 1992 resulting from aircraft are small relative to those caused by surface sources.* Although aerosol accumulation will grow with aviation fuel use, aerosol mass concentrations from aircraft in 2050 are projected to remain small compared to surface sources. Increases in soot tend to warm while increases in sulfate tend to cool the Earth's surface. The direct radiative forcing of sulfate and soot aerosols from aircraft is small compared to those of other aircraft emissions. Because aerosols influence the formation of clouds, the accumulation of aerosols from aircraft may play a role in enhanced cloud formation and change the radiative properties of clouds.

### 4.8. What are the Overall Climate Effects of Subsonic Aircraft?

*The climate impacts of different anthropogenic emissions can be compared using the concept of radiative forcing. The best estimate of the radiative forcing in 1992 by aircraft is 0.05 $Wm^{-2}$ or about 3.5% of the total radiative forcing by all anthropogenic activities. For the reference scenario (Fa1), the radiative forcing by aircraft in 2050 is 0.19 $Wm^{-2}$ or 5% of the radiative forcing in the mid-range IS92a scenario (3.8 times the value in 1992). According to the range of scenarios considered here, the forcing is projected to grow to 0.13 to 0.56 $Wm^{-2}$ in 2050, which is a factor of 1.5 less to a factor of 3 greater than that for Fa1 and from 2.6 to 11 times the value in 1992.* These estimates of forcing combine the effects from changes in concentrations of carbon dioxide, ozone, methane, water vapor, line-shaped contrails, and aerosols, but do not include possible changes in cirrus clouds.

Globally averaged values of the radiative forcing from different components in 1992 and in 2050 under the reference scenario (Fa1) are shown in Figure 2. Figure 2 indicates the best estimates of the forcing for each component and the two-thirds uncertainty range.[8] The derivation of these uncertainty ranges involves expert scientific judgment and may also include objective statistical models. The uncertainty range in the radiative forcing stated here combines the uncertainty in calculating the atmospheric change to greenhouse gases and aerosols with that of calculating radiative forcing. For additional cirrus clouds, only a range for the best estimate is given; this is not included in the total radiative forcing.

The state of scientific understanding is evaluated for each component. This is not the same as the confidence level expressed in previous IPCC documents. This evaluation is separate from the uncertainty range and is a relative appraisal of the scientific understanding for each component. The evaluation is based on the amount of evidence available to support the best estimate and its uncertainty, the degree of consensus in the scientific literature, and the scope of the analysis. The total radiative forcing under each of the six scenarios for the growth of aviation is shown in Figure 3 for the period 1990 to 2050.

The total radiative forcing due to aviation (without forcing from additional cirrus) is likely to lie within the range from 0.01 to 0.1 $Wm^{-2}$ in 1992, with the largest uncertainties coming from contrails and methane. Hence the total radiative forcing may be about 2 times larger or 5 times smaller than the best estimate. For any scenario at 2050, the uncertainty range of radiative forcing is slightly larger than for 1992, but the largest variations of projected radiative forcing come from the range of scenarios.

Over the period from 1992 to 2050, the overall radiative forcing by aircraft (excluding that from changes in cirrus clouds) for all scenarios in this report is a factor of 2 to 4 larger

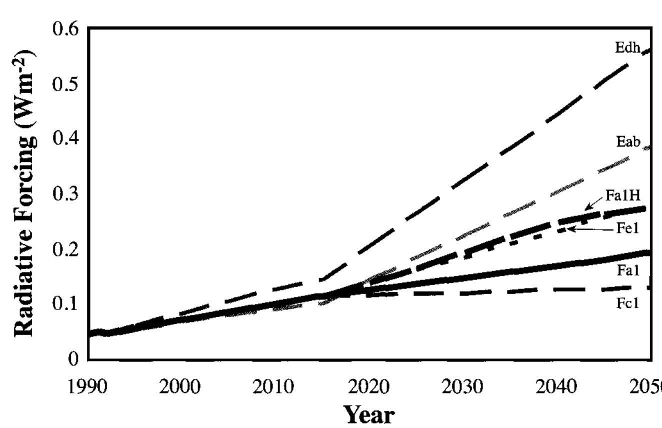


**Figure 3**: Estimates of the globally and annually averaged total radiative forcing (without cirrus clouds) associated with aviation emissions under each of six scenarios for the growth of aviation over the time period 1990 to 2050. (Fa2 has not been drawn because the difference from scenario Fa1 would not be discernible on the figure.)

[8] The two-thirds uncertainty range means there is a 67% probability that the true value falls within this range.

than the forcing by aircraft carbon dioxide alone. The overall radiative forcing for the sum of all human activities is estimated to be at most a factor of 1.5 larger than that of carbon dioxide alone.

The emissions of $NO_x$ cause changes in methane and ozone, with influence on radiative forcing estimated to be of similar magnitude but of opposite sign. However, as noted above, the geographical distribution of the aircraft ozone forcing is far more regional than that of the aircraft methane forcing.

The effect of aircraft on climate is superimposed on that caused by other anthropogenic emissions of greenhouse gases and particles, and on the background natural variability. The radiative forcing from aviation is about 3.5% of the total radiative forcing in 1992. It has not been possible to separate the influence on global climate change of aviation (or any other sector with similar radiative forcing) from all other anthropogenic activities. Aircraft contribute to global change approximately in proportion to their contribution to radiative forcing.

### *4.9. What are the Overall Effects of Subsonic Aircraft on UV-B?*

*Ozone, most of which resides in the stratosphere, provides a shield against solar ultraviolet radiation. The erythemal dose rate, defined as UV irradiance weighted according to how effectively it causes sunburn, is estimated to be decreased by aircraft in 1992 by about 0.5% at 45°N in July. For comparison, the calculated increase in the erythemal dose rate due to observed ozone depletion is about 4% over the period 1970 to 1992 at 45°N in July.*[9] *The net effect of subsonic aircraft appears to be an increase in column ozone and a decrease in UV radiation, which is mainly due to aircraft $NO_x$ emissions.* Much smaller changes in UV radiation are associated with aircraft contrails, aerosols, and induced cloudiness. In the Southern Hemisphere, the calculated effects of aircraft emission on the erythemal dose rate are about a factor of 4 lower than for the Northern Hemisphere.

*For the reference scenario (Fa1), the change in erythemal dose rate at 45°N in July in 2050 compared to a simulation with no aircraft is -1.3% (with a two-thirds uncertainty range from -0.7 to -2.6%).* For comparison, the calculated change in the erythemal dose rate due to changes in the concentrations of trace species, other than those from aircraft, between 1970 to 2050 at 45°N is about -3%, a decrease that is the net result of two opposing effects: (1) the incomplete recovery of stratospheric ozone to 1970 levels because of the persistence of long-lived halogen-containing compounds, and (2) increases in projected surface emissions of shorter lived pollutants that produce ozone in the troposphere.

[9] This value is based on satellite observations and model calculations. See **WMO,** 1999: *Scientific Assessment of Ozone Depletion: 1998.* Report No. 44, Global Ozone Research and Monitoring Project, World Meteorological Organization, Geneva, Switzerland, 732 pp.

## 5. What are the Current and Future Impacts of Supersonic Aviation on Radiative Forcing and UV Radiation?

*One possibility for the future is the development of a fleet of second generation supersonic, high speed civil transport (HSCT) aircraft, although there is considerable uncertainty whether any such fleet will be developed.* These supersonic aircraft are projected to cruise at an altitude of about 19 km, about 8 km higher than subsonic aircraft, and to emit carbon dioxide, water vapor, $NO_x$, $SO_x$, and soot into the stratosphere. $NO_x$, water vapor, and $SO_x$ from supersonic aircraft emissions all contribute to changes in stratospheric ozone. The radiative forcing of civil supersonic aircraft is estimated to be about a factor of 5 larger than that of the displaced subsonic aircraft in the Fa1H scenario. The calculated radiative forcing of supersonic aircraft depends on the treatment of water vapor and ozone in models. This effect is difficult to simulate in current models and so is highly uncertain.

Scenario Fa1H considers the addition of a fleet of civil supersonic aircraft that was assumed to begin operation in the year 2015 and grow to a maximum of 1,000 aircraft by the year 2040. For reference, the civil subsonic fleet at the end of the year 1997 contained approximately 12,000 aircraft. In this scenario, the aircraft are designed to cruise at Mach 2.4, and new technologies are assumed that maintain emissions of 5 g $NO_2$ per kg fuel (lower than today's civil supersonic aircraft which has emissions of about 22 g $NO_2$ per kg fuel). These supersonic aircraft are assumed to replace part of the subsonic fleet (11%, in terms of emissions in scenario Fa1). Supersonic aircraft consume more than twice the fuel per passenger-km compared to subsonic aircraft. *By the year 2050, the combined fleet (scenario Fa1H) is projected to add a further 0.08 $Wm^{-2}$ (42%) to the 0.19 $Wm^{-2}$ radiative forcing from scenario Fa1 (see Figure 4). Most of this additional forcing is due to accumulation of stratospheric water vapor.*

The effect of introducing a civil supersonic fleet to form the combined fleet (Fa1H) is also to reduce stratospheric ozone and increase erythemal dose rate. The maximum calculated effect is at 45°N where, in July, the ozone column change in 2050 from the combined subsonic and supersonic fleet relative to no aircraft is -0.4%. The effect on the ozone column of the supersonic component by itself is -1.3% while the subsonic component is +0.9%.

*The combined fleet would change the erythemal dose rate at 45°N in July by +0.3% compared to the 2050 atmosphere without aircraft. The two-thirds uncertainty range for the combined fleet is -1.7% to +3.3%. This may be compared to the projected change of -1.3% for Fa1.* Flying higher leads to larger ozone column decreases, while flying lower leads to smaller ozone column decreases and may even result in an ozone column increase for flight in the lowermost stratosphere. In addition, emissions from supersonic aircraft in the Northern Hemisphere stratosphere may be transported to the Southern Hemisphere where they cause ozone depletion.

Radiative Forcing from Aircraft in 2050 with Supersonic Fleet

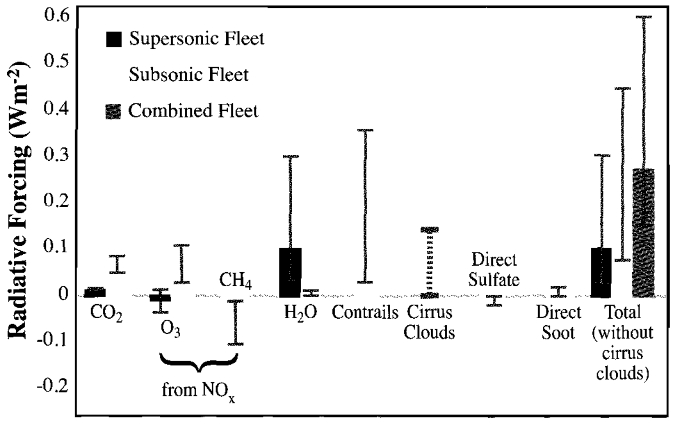


**Figure 4**: Estimates of the globally and annually averaged radiative forcing from a combined fleet of subsonic and supersonic aircraft (in $Wm^{-2}$) due to changes in greenhouse gases, aerosols, and contrails in 2050 under the scenario Fa1H. In this scenario, the supersonic aircraft are assumed to replace part of the subsonic fleet (11%, in terms of emissions in scenario Fa1). The bars indicate the best estimate of forcing while the line associated with each bar is a two-thirds uncertainty range developed using the best knowledge and tools available at the present time. (The two-thirds uncertainty range means that there is a 67% probability that the true value falls within this range.) The available information on cirrus clouds is insufficient to determine either a best estimate or an uncertainty range; the dashed line indicates a range of possible best estimates. The estimate for total forcing does not include the effect of changes in cirrus cloudiness. The uncertainty estimate for the total radiative forcing (without additional cirrus) is calculated as the square root of the sums of the squares of the upper and lower ranges. The level of scientific understanding for the supersonic components are carbon dioxide, "good;" ozone, "poor;" and water vapor, "poor."

## 6. What are the Options to Reduce Emissions and Impacts?

*There is a range of options to reduce the impact of aviation emissions, including changes in aircraft and engine technology, fuel, operational practices, and regulatory and economic measures. These could be implemented either singly or in combination by the public and/or private sector. Substantial aircraft and engine technology advances and the air traffic management improvements described in this report are already incorporated in the aircraft emissions scenarios used for climate change calculations. Other operational measures, which have the potential to reduce emissions, and alternative fuels were not assumed in the scenarios. Further technology advances have the potential to provide additional fuel and emissions reductions. In practice, some of the improvements are expected to take place for commercial reasons. The timing and scope of regulatory, economic, and other options may affect the introduction of improvements and may affect demand for air transport. Mitigation options for water vapor and cloudiness have not been fully addressed.*

Safety of operation, operational and environmental performance, and costs are dominant considerations for the aviation industry when assessing any new aircraft purchase or potential engineering or operational changes. The typical life expectancy of an aircraft is 25 to 35 years. These factors have to be taken into account when assessing the rate at which technology advances and policy options related to technology can reduce aviation emissions.

### *6.1. Aircraft and Engine Technology Options*

*Technology advances have substantially reduced most emissions per passenger-km. However, there is potential for further improvements. Any technological change may involve a balance among a range of environmental impacts.*

Subsonic aircraft being produced today are about 70% more fuel efficient per passenger-km than 40 years ago. The majority of this gain has been achieved through engine improvements and the remainder from airframe design improvement. A 20% improvement in fuel efficiency is projected by 2015 and a 40 to 50% improvement by 2050 relative to aircraft produced today. The 2050 scenarios developed for this report already incorporate these fuel efficiency gains when estimating fuel use and emissions. Engine efficiency improvements reduce the specific fuel consumption and most types of emissions; however, contrails may increase and, without advances in combuster technology, $NO_x$ emissions may also increase.

Future engine and airframe design involves a complex decision-making process and a balance of considerations among many factors (e.g., carbon dioxide emissions, $NO_x$ emissions at ground level, $NO_x$ emissions at altitude, water vapor emissions, contrail/cirrus production, and noise). These aspects have not been adequately characterized or quantified in this report.

Internationally, substantial engine research programs are in progress, with goals to reduce Landing and Take-off cycle (LTO) emissions of $NO_x$ by up to 70% from today's regulatory standards, while also improving engine fuel consumption by 8 to 10%, over the most recently produced engines, by about 2010. Reduction of $NO_x$ emissions would also be achieved at cruise altitude, though not necessarily by the same proportion as for LTO. Assuming that the goals can be achieved, the transfer of this technology to significant numbers of newly produced aircraft will take longer—typically a decade. Research programs addressing $NO_x$ emissions from supersonic aircraft are also in progress.

### *6.2. Fuel Options*

*There would not appear to be any practical alternatives to kerosene-based fuels for commercial jet aircraft for the next* *several decades. Reducing sulfur content of kerosene will reduce $SO_x$ emissions and sulfate particle formation.*

Jet aircraft require fuel with a high energy density, especially for long-haul flights. Other fuel options, such as hydrogen, may be viable in the long term, but would require new aircraft designs and new infrastructure for supply. Hydrogen fuel would eliminate emissions of carbon dioxide from aircraft, but would increase those of water vapor. The overall environmental impacts and the environmental sustainability of the production and use of hydrogen or any other alternative fuels have not been determined.

The formation of sulfate particles from aircraft emissions, which depends on engine and plume characteristics, is reduced as fuel sulfur content decreases. While technology exists to remove virtually all sulfur from fuel, its removal results in a reduction in lubricity.

### 6.3. Operational Options

*Improvements in air traffic management (ATM) and other operational procedures could reduce aviation fuel burn by between 8 and 18%. The large majority (6 to 12%) of these reductions comes from ATM improvements which it is anticipated will be fully implemented in the next 20 years. All engine emissions will be reduced as a consequence. In all aviation emission scenarios considered in this report the reductions from ATM improvements have already been taken into account. The rate of introduction of improved ATM will depend on the implementation of the essential institutional arrangements at an international level.*

Air traffic management systems are used for the guidance, separation, coordination, and control of aircraft movements. Existing national and international air traffic management systems have limitations which result, for example, in holding (aircraft flying in a fixed pattern waiting for permission to land), inefficient routings, and sub-optimal flight profiles. These limitations result in excess fuel burn and consequently excess emissions.

For the current aircraft fleet and operations, addressing the above-mentioned limitations in air traffic management systems could reduce fuel burned in the range of 6 to 12%. It is anticipated that the improvement needed for these fuel burn reductions will be fully implemented in the next 20 years, provided that the necessary institutional and regulatory arrangements have been put in place in time. The scenarios developed in this report assume the timely implementation of these ATM improvements, when estimating fuel use.

Other operational measures to reduce the amount of fuel burned per passenger-km include increasing load factors (carrying more passengers or freight on a given aircraft), eliminating non-essential weight, optimizing aircraft speed, limiting the use of auxiliary power (e.g., for heating, ventilation), and reducing taxiing. The potential improvements in these operational measures could reduce fuel burned, and emissions, in the range 2 to 6%.

Improved operational efficiency may result in attracting additional air traffic, although no studies providing evidence on the existence of this effect have been identified.

### 6.4. Regulatory, Economic, and Other Options

*Although improvements in aircraft and engine technology and in the efficiency of the air traffic system will bring environmental benefits, these will not fully offset the effects of the increased emissions resulting from the projected growth in aviation. Policy options to reduce emissions further include more stringent aircraft engine emissions regulations, removal of subsidies and incentives that have negative environmental consequences, market-based options such as environmental levies (charges and taxes) and emissions trading, voluntary agreements, research programs, and substitution of aviation by rail and coach. Most of these options would lead to increased airline costs and fares. Some of these approaches have not been fully investigated or tested in aviation and their outcomes are uncertain.*

Engine emissions certification is a means for reducing specific emissions. The aviation authorities currently use this approach to regulate emissions for carbon monoxide, hydrocarbons, $NO_x$, and smoke. The International Civil Aviation Organization has begun work to assess the need for standards for aircraft emissions at cruise altitude to complement existing LTO standards for $NO_x$ and other emissions.

Market-based options, such as environmental levies (charges and taxes) and emissions trading, have the potential to encourage technological innovation and to improve efficiency, and may reduce demand for air travel. Many of these approaches have not been fully investigated or tested in aviation and their outcomes are uncertain.

Environmental levies (charges and taxes) could be a means for reducing growth of aircraft emissions by further stimulating the development and use of more efficient aircraft and by reducing growth in demand for aviation transportation. Studies show that to be environmentally effective, levies would need to be addressed in an international framework.

Another approach that could be considered for mitigating aviation emissions is emissions trading, a market-based approach which enables participants to cooperatively minimize the costs of reducing emissions. Emissions trading has not been tested in aviation though it has been used for sulfur dioxide ($SO_2$) in the United States of America and is possible for ozone-depleting substances in the Montreal Protocol. This approach is one of the provisions of the Kyoto Protocol where it applies to Annex B Parties.

Voluntary agreements are also currently being explored as a means of achieving reductions in emissions from the aviation sector. Such agreements have been used in other sectors to reduce greenhouse gas emissions or to enhance sinks.

Measures that can also be considered are removal of subsidies or incentives which would have negative environmental consequences, and research programs.

Substitution by rail and coach could result in the reduction of carbon dioxide emissions per passenger-km. The scope for this reduction is limited to high density, short-haul routes, which could have coach or rail links. Estimates show that up to 10% of the travelers in Europe could be transferred from aircraft to high-speed trains. Further analysis, including trade-offs between a wide range of environmental effects (e.g., noise exposure, local air quality, and global atmospheric effects) is needed to explore the potential of substitution.

## 7. Issues for the Future

*This report has assessed the potential climate and ozone changes due to aircraft to the year 2050 under different scenarios. It recognizes that the effects of some types of aircraft emissions are well understood. It also reveals that the effects of others are not, because of the many scientific uncertainties. There has been a steady improvement in characterizing the potential impacts of human activities, including the effects of aviation on the global atmosphere. The report has also examined technological advances, infrastructure improvements, and regulatory or market-based measures to reduce aviation emissions. Further work is required to reduce scientific and other uncertainties, to understand better the options for reducing emissions, to better inform decisionmakers, and to improve the understanding of the social and economic issues associated with the demand for air transport.*

There are a number of key areas of scientific uncertainty that limit our ability to project aviation impacts on climate and ozone:

- The influence of contrails and aerosols on cirrus clouds
- The role of $NO_x$ in changing ozone and methane concentrations
- The ability of aerosols to alter chemical processes
- The transport of atmospheric gases and particles in the upper troposphere/lower stratosphere
- The climate response to regional forcings and stratospheric perturbations.

There are a number of key socio-economic and technological issues that need greater definition, including *inter alia* the following:

- Characterization of demand for commercial aviation services, including airport and airway infrastructure constraints and associated technological change
- Methods to assess external costs and the environmental benefits of regulatory and market-based options
- Assessment of the macroeconomic effects of emission reductions in the aviation industry that might result from mitigation measures
- Technological capabilities and operational practices to reduce emissions leading to the formation of contrails and increased cloudiness
- The understanding of the economic and environmental effects of meeting potential stabilization scenarios (for atmospheric concentrations of greenhouse gases), including measures to reduce emissions from aviation and also including such issues as the relative environmental impacts of different transportation modes.

# Aircraft Emissions: Current Inventories and Future Scenarios

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9

# Aircraft Emissions: Current Inventories and Future Scenarios

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## CONTENTS

# EXECUTIVE SUMMARY

- Three-dimensional (latitude, longitude, altitude) global inventories of civil and military aircraft fuel burned and emissions have been developed for the United States National Aeronautics and Space Administration (NASA) for the years 1976, 1984, and 1992, and by the European Abatement of Nuisances Caused by Air Transport (ANCAT)/European Commission (EC) Working Group and the Deutsches Zentrum für Luft- und Raumfahrt (DLR) for 1991/92. For 1992, the results of the inventory calculations are in good agreement, with total fuel used by aviation calculated to be 129.3 Tg (DLR), 131.2 Tg (ANCAT), and 139.4 Tg (NASA). Total emissions of $NO_x$ (as $NO_2$) in 1992 were calculated to range from 1.7 Tg (NASA) to 1.8 Tg (ANCAT and DLR).

- Forecasts of air travel demand and technology developed by NASA and ANCAT for 2015 have been used to create three-dimensional (3-D) data sets of fuel burn and $NO_x$ emissions for purposes of modeling the near-term effects of aircraft. The NASA 2015 forecast results in a global fuel burn of 309 Tg, with a $NO_x$ emission of 4.1 Tg (as $NO_2$); the global emission index, $EI(NO_x)$ (g $NO_x$/kg fuel), is 13.4. In contrast, the ANCAT 2015 forecast results in lower values—a global fuel burn of 287 Tg, an emission of 3.5 Tg of $NO_x$, and a global emission index of 12.3. The differences arise from the distribution of air travel demand and technology assumptions.

- Long-term emission scenarios for $CO_2$ and $NO_x$ from subsonic aviation in 2050 have been constructed by the International Civil Aviation Organization (ICAO) Forecasting and Economic Support Group (FESG); the United Kingdom Department of Trade and Industry (DTI); and the Environmental Defense Fund (EDF), whose projections extend to 2100. The FESG and EDF scenarios used the Intergovernmental Panel on Climate Change (IPCC) IS92 scenarios for economic growth to project future air traffic demand, though with different approaches to the relative importance of gross domestic product (GDP) and population. Each group also makes different assumptions about projected improvements in fleet fuel efficiency and $NO_x$ reduction technology. In addition, the Massachusetts Institute of Technology (MIT) has projected emissions from a "high speed" sector that includes aviation, and the World Wide Fund for Nature (WWF) has published a projection of aviation emissions for the year 2041.

- All future scenarios were constructed by assuming that the necessary infrastructure (e.g., airports, air traffic control) will be developed as needed and that fuel supplies will be available. System capacity constraints, if any, have not been evaluated.

- Future scenarios predict fuel use and $NO_x$ emissions that vary over a wide range, depending on the economic growth scenario and model used for the calculations. Although none of the scenarios are considered impossible as outcomes for 2050, some of the EDF high-growth scenarios are believed to be less plausible. The FESG low-growth scenarios, though plausible in terms of achievability, use traffic estimates that are very likely to be exceeded given the present state of the industry and planned developments.

- The 3-D gridded outputs from all of the FESG 2050 scenarios and from the DTI 2050 scenario are suitable for use as input to chemical transport models and may also be used to calculate the effect of aviation $CO_2$ emissions. The FESG scenarios project aviation fuel use in 2050 to be in the range of 471–488 Tg, with corresponding $NO_x$ emissions of 7.2 and 5.5 Tg (as $NO_2$) for IS92a, depending on the technology scenario; 268–277 Tg fuel and $NO_x$ of 4.0 and 3.1 Tg for IS92c; and 744–772 Tg fuel and $NO_x$ of 11.4 and 8.8 Tg for IS92e. (For all of the individual FESG IS92-based scenarios, higher fuel usage—thus $CO_2$ emissions—were a result of the more aggressive $NO_x$ reduction technology assumed). The DTI scenario projects aviation fuel use in 2050 to be 633 Tg, with $NO_x$ emissions at 4.5 Tg.

- As a result of higher projected fuel usage, EDF projections of $CO_2$ emissions are all higher than those of FESG by factors of approximately 2.4 to 4.3 for IS92a, 3.1 to 5.7 for IS92c, and 1.7 to 3.1 for IS92e. Results from EDF scenarios based on IS92a and IS92d are suitable for use in calculating the effect of $CO_2$ emissions as sensitivity analyses; the latter scenario projects $CO_2$ emissions levels from aviation 2.2 times greater in 2050 than the highest of the FESG scenarios.

- The effects of a fleet of high-speed civil transport (HSCT) aircraft on fuel burned and $NO_x$ emissions in the year 2050 were calculated using the FESG year 2050 subsonic inventories as a base. A fleet of 1,000 HSCTs operating with a program goal $EI(NO_x)$ of 5 in 2050 was calculated to increase global fuel burned by 12–18% and reduce global $NO_x$ by 1–2% (depending on the scenario chosen), assuming that low-$NO_x$ HSCTs displace traffic from the higher $NO_x$ subsonic fleet. A fleet of 1,000 HSCT aircraft was chosen to evaluate the effect of a large fleet; it does not constitute a forecast of the size of an HSCT fleet in 2050.

- The simplifying assumptions used in calculating all of the historical and present-day 3-D inventories (1976 through 1992)—great circle routing, no winds, standard temperatures, no cargo payload—cause a systematic underestimate of fuel burned (therefore emissions produced) by aviation on the order of 15%, so calculated values were scaled up accordingly. By 2015, we assume that the introduction of advanced air traffic management systems will reduce this underestimate to approximately 5%. Full implementation of these systems by 2050 should reduce the error somewhat further, but given the wide range of year 2050 scenario projections, adjustments to calculated fuel values in 2050 were not considered to be necessary.

## 9.1. Introduction

The nature and composition of aircraft emissions has been described in Chapter 1, and their effects on the composition of the atmosphere are described in Chapters 2 and 3. Chapter 4 uses aircraft emissions data in modeling studies to provide chemical perturbations that feed into the ultraviolet (UV) irradiance and radiative forcing calculations presented in Chapters 5 and 6, respectively. In this chapter, the aircraft emissions data that were used in calculations described in Chapters 4 and 6 are presented and discussed.

Compilation of global inventories of aircraft $NO_x$ emissions has been driven by requirements for global modeling studies of the effects of these emissions on stratospheric and tropospheric ozone ($O_3$). Aircraft carbon dioxide ($CO_2$) emissions are easily calculated from total fuel burned. Early studies used one- (1-D) and two-dimensional (2-D) models of the atmosphere (see Section 2.2.1). Most of these early studies considered effects on the stratosphere (e.g., COMESA, 1975), but some also included assessments of the (then) current subsonic fleet on the upper troposphere and lower stratosphere (e.g., Hidalgo and Crutzen, 1977; Derwent, 1982). An early height- and latitude-dependent emissions inventory of aircraft $NO_x$ was given by Bauer (1979), based on earlier work by A.D. Little (1975). This work was used by Derwent (1982) in a 2-D modeling study of aircraft $NO_x$ emissions in the troposphere.

Later estimations of global aircraft emissions of $NO_x$ were still made by relatively simple methods, using fuel usage and assumed EI($NO_x$) (e.g., Nüßer and Schmitt, 1990; Beck *et al.*, 1992). Concerted efforts were subsequently made by a number of groups to construct high-quality global 3-D inventories of aircraft emissions. Such work was undertaken for a variety of programs and purposes: United Kingdom input to ICAO Technical Working Groups (McInnes and Walker, 1992); the U.S. Atmospheric Effects of Stratospheric Aircraft (AESA) Program (Wuebbles *et al.*, 1993); the German "Schadstoffe in der Luftfahrt" Program (Schmitt and Brunner, 1997); and the ANCAT/EC Emissions Database Group (ANCAT/EC, 1995), which combined European efforts to produce an aircraft $NO_x$ inventory for the AERONOX Program (Gardner *et al.*, 1997). Subsequently, methodologies for the production of global 3-D inventories of present-day aircraft $NO_x$ emissions (based on 1991–92) have been refined and have produced results that have largely superseded earlier work. These inventories cover the 1976–92 time period and have been extended to the 2015 forecast period. These gridded inventories—which calculate aviation emissions as distributed around the Earth in terms of latitude, longitude, and altitude—have been produced by NASA, DLR, and ANCAT/EC for national and international work programs (Baughcum *et al.*, 1996a,b; Schmitt and Brunner, 1997; Gardner, 1998).

This chapter is not the first attempt to synthesize information on aircraft emissions inventories; earlier assessments were made by the World Meteorological Organization (WMO)/ United National Environment Programme (UNEP) (1995) Scientific Assessment of Ozone Depletion, ICAO's Committee on Aviation Environmental Protection (CAEP) Working Group 3 (CAEP/WG3, 1995), the NASA Advanced Subsonic Technology Program (Friedl, 1997), and the European Scientific Assessment of the Atmospheric Effects of Aircraft Emissions (Brasseur *et al.*, 1998).

Any assessment of present and potential future effects of subsonic and supersonic air transport emissions relies heavily on input emissions data. Thus, considerable effort has been expended on understanding the accuracy of present-day inventories and the construction of forecasts and scenarios. Forecasts are quite distinct from scenarios, as noted in Chapter 1. Forecasts of aviation emissions for a 20–25 year time frame are generally considered possible, whereas such confidence is not the case for longer time frames. Thus, scenarios generally rely on many more assumptions and are less specific than forecasts.

In planning this Special Report, it was clear that there were no gridded emission scenarios of $NO_x$ emissions from subsonic aircraft for the year 2050 that could be used as input to 3-D chemical transport models (see Chapters 2 and 4). The IPCC made a request to ICAO to prepare 3-D $NO_x$ scenarios, which was carried out under the auspices of ICAO's FESG (CAEP/4-FESG, 1998). The UK DTI also responded to this requirement, producing an independent 3-D $NO_x$ scenario for 2050 (Newton and Falk, 1997). The EDF had also published scenarios of aircraft emissions of $NO_x$ and $CO_2$ extending to 2100 (Vedantham and Oppenheimer, 1994, 1998), but these scenarios were not gridded; thus, although the aviation $CO_2$ scenarios could be used in radiative forcing calculations (see Chapter 6), the $NO_x$ scenarios could not be used to calculate $O_3$ perturbations and subsequent radiative forcing. Other scenario data exist for aircraft emissions, including those from WWF (Barrett, 1994) and MIT (Schafer and Victor, 1997). As with the EDF data, these scenarios were not gridded for $NO_x$ emissions, therefore could not be used in $O_3$ perturbation calculations in Chapter 4. Furthermore, the MIT data do not explicitly represent aircraft emissions; instead, they cover high-speed transport modes, including some surface transportation modes.

HSCT scenarios prepared for NASA's AESA Program are considered distinct from subsonic scenarios; these HSCT scenarios represent a technology that does not yet exist but might be developed. Therefore, the HSCT scenarios represent a quite different set of assumptions from other long-term scenarios, which only consider continued development of a subsonic fleet. The HSCT scenarios were used in modeling studies (Chapters 4 and 6) as sensitivity analyses for studying the effects of their emissions on stratospheric $O_3$.

In this chapter, methodologies of inventory and forecast construction are compared, and a review and assessment of long-term scenarios and their implicit assumptions provided. This is the first detailed consideration of long-term scenarios and their implications.

By way of background, Section 9.2 provides an overview of factors that affect aircraft emissions, such as market demand for air travel and developments in the technology. The aircraft emissions data discussed in this chapter are of four distinct types: Historical inventories (e.g., for 1976 and 1984); inventories that represent the "present day" (i.e., 1991–92); forecasts for 2015; and long-term scenarios for 2050 and beyond. The methodologies and a comparison of historical, present-day, and forecast inventories are presented in Section 9.3. Section 9.4 describes and comments on available long-term scenarios for 2050 and beyond. Scenarios of high-speed civil transport (HSCT) that incorporate certain assumptions about the development of a supersonic fleet and its impact on the subsonic fleet are presented separately in Section 9.5. Finally, Section 9.6 discusses underlying assumptions and drivers of long-term subsonic scenarios. The plausibility of the assumptions are also considered in terms of implications for fleet size, infrastructure requirements, and global fossil-fuel availability.

## 9.2. Factors Affecting Aircraft Emissions

### *9.2.1. Demand for Air Travel*

In the past 50 years, the air transport industry has experienced rapid expansion as the world economy has grown and the technology of air transport has developed to its present state. The result has been a steady decline in costs and fares, which has further stimulated traffic growth. As an example of this growth, the output of the industry (measured in terms of tonne-km performed) has increased by a factor of 23 since 1960; total GDP, which is the broadest available measure of world output, increased by a factor of 3.8 over the same period (ICAO, 1997a).

Although growth in world air traffic has been much greater than world economic growth, economic theory and analytical studies indicate that there is a high correlation between the two, and most forecasts of aviation demand are based on the premise that the demand for air transport is determined primarily by economic development. Statistical analyses have shown that growth in GDP now explains about two-thirds of air travel growth, reflecting increasing commercial and business activity and increasing personal income and propensity to travel. Demand for air freight service is also primarily a function of economic growth. Air travel growth in excess of GDP growth is usually explained by other economic and structural factors:

- Improvement in service offerings as routes and frequencies and infrastructure are added, stimulation from reductions in airline fares as costs decline, and increasing trade and the globalization of business (Boeing, 1998)
- Population and income distribution (Vedantham and Oppenheimer, 1998)
- Travel behavior, including travel time budgets and travel costs (Zahavi, 1981; Schafer and Victor, 1997).

Changes in technology and in the regulatory environment have also had great effects on the growth in air travel demand. The modern era of air transportation began in the 1960s, driven by the replacement of piston-engined aircraft with jet aircraft that increased the speed, reliability, and comfort of air travel while reducing the cost of operation. The continuing trend of declining fares (as measured in constant dollars) began in this period. In real terms, fares have declined by almost 2% per year since 1960. Deregulation of airline services in the United States in 1978 allowed airlines to improve services by expanding their route systems and reduce average costs by greatly increasing the efficiency of scheduling and aircraft use. Trends toward liberalization of airline services in Europe and elsewhere will continue to increase airline efficiency.

Sharp increases in oil prices have had important (though temporary) effects on traffic demand. In addition to an adverse effect on the world economy, the 10-fold increase in crude oil prices in 1973–74 and further escalation in 1979–81 (since ameliorated) greatly increased aviation fuel prices. Air fares increased in response to higher costs, with a resulting decline in demand growth rates.

Figure 9-1 provides evidence of the relationship between the economy and traffic demand by illustrating fluctuations in the rate of growth of each from 1960 to the present. The economic recessions of 1974–75, 1979–82 (largely caused by the increase in oil prices), and 1990–91 (the Gulf War) and their impact on air traffic are clearly visible.

The growth rate in global passenger demand over the past 35 years is shown in Figure 9-2. Freight traffic, approximately 80% of which is carried in the bellies of passenger airplanes, has also grown over the same time period. The declining trend in the rate of growth as the size of the industry has increased by more than 20-fold is a natural result of the total size of the industry (it is difficult to sustain an "infant industry" growth rate as size increases) and a maturing of certain markets—primarily those in the developed world—that dominate the statistics.

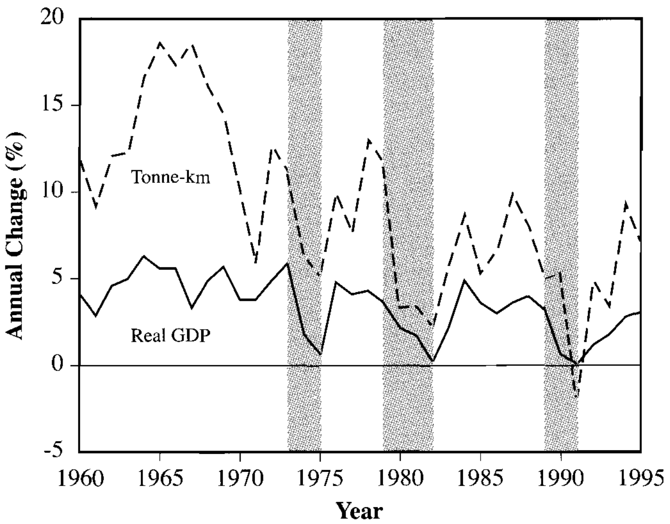


**Figure 9-1**: Relationship between economic growth and traffic demand growth (IMF, WEFA, ICAO Reporting Form A-1).

Changes in demand in regional markets are given in Table 9-1 for the period 1970–95. Over this period, global traffic measured in revenue passenger kilometers (RPK) increased by a factor of 4.6 (Boeing, 1996). Table 9-1 is ordered by 1995 regional RPK value.

### *9.2.2. Developments in Technology*

The trend in fuel efficiency of jet aircraft over time has been one of almost continuous improvement; fuel burned per seat in today's new aircraft is 70% less than that of early jets. About 40% of the improvement has come from engine efficiency improvements and 30% from airframe efficiency improvements (Figure 9-3, after Figure III-A-1 in Albritton *et. al*, 1997).

The growth rate of fuel consumed by aviation therefore has been lower than the growth in demand. Improvement in engine fuel efficiency has come mainly from the increasing use of modern high-bypass engine technology that relies on increasing engine pressure ratios and higher temperature combustors as a means to increase engine efficiency. These trends have resulted in drastic decreases in emissions of carbon monoxide (CO) and unburned hydrocarbons (HC), though they tend to increase emissions of oxides of nitrogen ($NO_x$). As a result, total $NO_x$ emissions from aircraft are growing faster than fuel consumption (see Figure 9-4, from NASA emissions inventories discussed in Section 9.3). A discussion of the technology required to reduce $NO_x$ emissions while continuing to improve engine efficiency appears in Chapter 7.

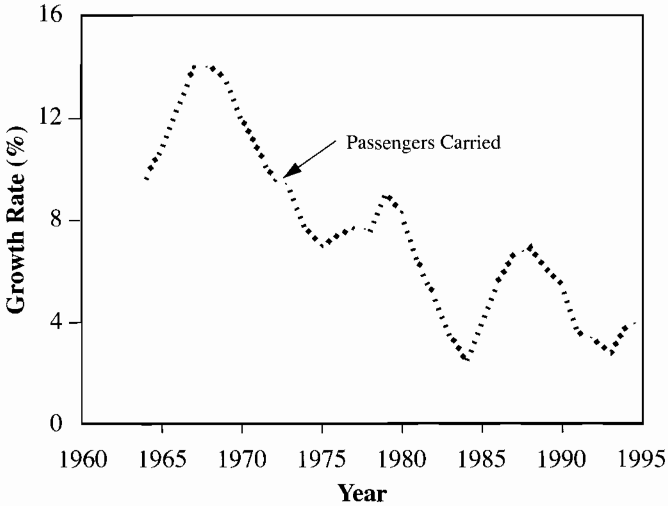


**Figure 9-2**: Growth rate of passengers carried (ICAO Reporting Form A-1). Note the assumption of 5-year moving average of annual growth rates, excluding operations in the Commonwealth of Independent States (CIS).

***Table 9-1**: Regional share of total demand.*

| Regional Traffic Flow | 1970 RPK x $10^9$ | 1995 RPK x $10^9$ | 1970–95 Growth Factor | 1970 Market Share | 1995 Market Share | 1970–95 Change in Share |
|---|---|---|---|---|---|---|
| Intra North America | 190.897 | 697.880 | 3.7 | 34.6% | 27.5% | -7.1% |
| Intra Europe | 61.275 | 317.099 | 5.2 | 11.1% | 12.5% | 1.4% |
| North America – Europe | 72.143 | 277.909 | 3.9 | 13.1% | 11.0% | -2.1% |
| China Domestic/Intra Asia/Intra Oceania | 10.234 | 207.405 | 20.3 | 1.9% | 8.2% | 6.3% |
| North America – Asia/Oceania | 14.760 | 188.799 | 12.8 | 2.7% | 7.4% | 4.8% |
| Europe – Asia | 6.732 | 134.343 | 20.0 | 1.2% | 5.3% | 4.1% |
| Asia – India/Africa/Middle East | 13.959 | 115.204 | 8.3 | 2.5% | 4.5% | 2.0% |
| North America – Latin America | 16.087 | 75.538 | 4.7 | 2.9% | 3.0% | 0.1% |
| Europe – Latin America | 7.124 | 73.090 | 10.3 | 1.3% | 2.9% | 1.6% |
| Domestic Former Soviet Union | 75.496 | 67.603 | 0.9 | 13.7% | 2.7% | -11.0% |
| Japan Domestic | 8.181 | 61.607 | 7.5 | 1.5% | 2.4% | 0.9% |
| Europe – Africa | 18.478 | 61.045 | 3.3 | 3.4% | 2.4% | -0.9% |
| Intra/Domestic Latin America | 13.432 | 55.331 | 4.1 | 2.4% | 2.2% | -0.3% |
| Europe – Middle East | 9.838 | 41.224 | 4.2 | 1.8% | 1.6% | -0.2% |
| Intra/Domestic Middle East – Africa | 5.065 | 39.213 | 7.7 | 0.9% | 1.5% | 0.6% |
| International Former Soviet Union | 3.677 | 29.508 | 8.0 | 0.7% | 1.2% | 0.5% |
| Indian Subcontinent – Asia/Middle East/Oceania | 3.249 | 29.500 | 9.1 | 0.6% | 1.2% | 0.6% |
| Europe – Indian Subcontinent | 2.333 | 19.858 | 8.5 | 0.4% | 0.8% | 0.4% |
| Intra/Domestic Africa | 5.826 | 16.808 | 2.9 | 1.1% | 0.7% | -0.4% |
| Intra Indian Subcontinent | 3.215 | 13.218 | 4.1 | 0.6% | 0.5% | -0.1% |
| North America – Africa/Middle East | 1.149 | 10.777 | 9.4 | 0.2% | 0.4% | 0.2% |
| U.S. Military Airlift | 8.112 | 3.605 | 0.4 | 1.5% | 0.1% | -1.3% |
| **Total** | **551.262** | **2536.561** | **4.6** | **100.0%** | **100.0%** | **0.0%** |

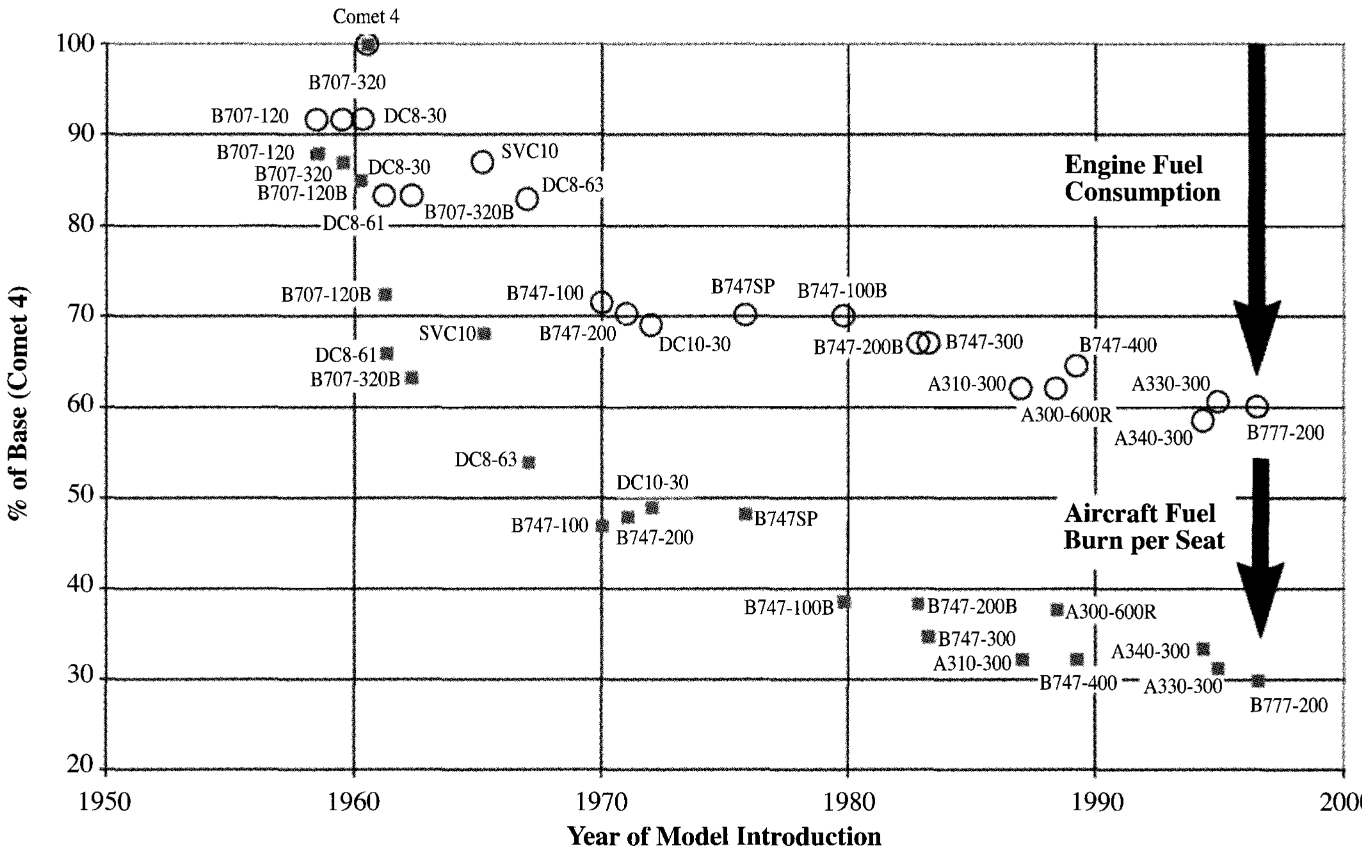


**Figure 9-3**: Trend in transport aircraft fuel efficiency.

## 9.3. Historical, Present-Day, and 2015 Forecast Emissions Inventories

Studies on the effects of $CO_2$ emissions from aircraft on radiative forcing require only a knowledge of total emissions. However, to examine the potential effects of other emissions from aviation (e.g., those considered in Chapter 4), estimates of the amount and the distribution of emissions are required. Such 3-D inventories for present and projected future aviation operations have been produced under the aegis of NASA's Atmospheric Effects of Aviation Project (AEAP), the European Civil Aviation Conference's ANCAT and EC Emissions Inventory Database Group (EIDG), and DLR.

These inventories consist of calculated aircraft emissions distributed over the world's airspace by latitude, longitude, and altitude. Historical inventories of aviation emissions have been produced for 1976 and 1984 by NASA. Present-day and 2015 forecast inventories (where present-day is taken to be the most recent available—1991–92) have been produced by NASA, ANCAT, and DLR. DLR has also produced emissions inventories of scheduled international aviation only for each year from 1982 through 1992, and for total scheduled aviation for 1986 and 1989. DLR has also constructed a four-dimensional (4-D) inventory with diurnal cycles for scheduled aviation in March 1992.

All of the aforementioned 3-D emissions inventories have a common approach of combining a database of global air traffic (fleet mix, city-pairs served, and flight frequencies) with a set of assumptions about flight operations (flight profiles and routing) and a method to calculate altitude-dependent emissions of aircraft/engine combinations in the fleet. Figure 9-5 shows how these processes are combined.

All of the historical, present-day, and 2015 forecast inventories considered in this section assume idealized flight routings and profiles, with no winds or system delays. Thus, minimum

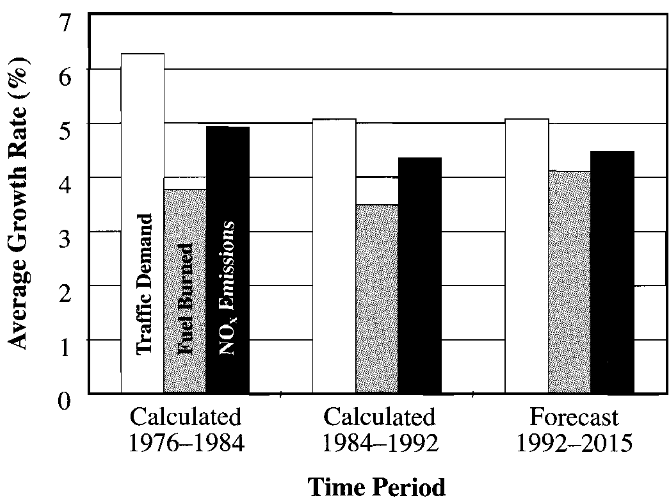


**Figure 9-4**: Comparison of growth rates for civil traffic, fuel consumption, and $NO_x$ emissions.

fuel burn and emissions possible for each flight operation are implicit, given the onboard load assumed. Simplifying assumptions for military operations vary according to aircraft type.

### *9.3.1. NASA, ANCAT/EC2, and DLR Historical and Present-Day Emissions Inventories*

The NASA, ANCAT, and DLR 3-D inventories adopt a similar overall approach but differ in some of the components and data used. This section describes the common approaches and explains the differences. More detailed information appears in the source material for these inventories (Baughcum *et al.*, 1996a,b; Schmitt and Brunner, 1997; Gardner, 1998).

All of the inventories use a "bottom-up" approach in which an aircraft movement database was compiled, aircraft/engine combinations in operation were identified (to differing levels of detail), and calculations of fuel burned and emissions along great-circle paths between cities were made. Flight operation data were calculated as the number of departures for each city pair by aircraft and engine type—which, combined with performance and emissions data, gave fuel burned and emissions by altitude along each route. This approach resulted in data on fuel burned and emissions of $NO_x$ (as $NO_2$) on a 3-D grid for each flight. In addition, the NASA inventories provide 3-D distributions of CO and total HC. NASA and ANCAT inventories were calculated on a 1° longitude x 1° latitude x 1-km altitude resolution, whereas the DLR inventory used a 2.8° longitude x 2.8° latitude horizontal resolution.

Different approaches were taken for constructing underlying traffic movements databases. The NASA inventories use scheduled jet and turboprop aviation operations for the years 1976, 1984, and 1992 (Baughcum *et al.*, 1996a,b). Movements for charter carriers, military operations, general aviation, and the domestic fleets of the former Soviet Union (FSU) and the People's Republic of China were estimated separately (Landau *et al.*, 1994; Metwally, 1995; Mortlock and Van Alstyne, 1998). Military aircraft contributions to emissions were calculated by estimating the flight activity of each type of military aircraft by country. The 1976 and 1984 NASA inventories were based on operations for 1 month in each quarter of the year, whereas the 1992 inventory compiled movements on a monthly basis to reflect the seasonality of aviation operations.

The ANCAT approach used a combination of air traffic control (ATC) data and scheduled movements, favoring ATC data where available (Gardner, 1998). Where ATC data were unavailable, scheduled data were taken from the ABC Travel Guide (ABC), the Official Airline Guide (OAG), the Aeroflot time table, and a German study of Chinese domestic aircraft movements. Only jet aircraft were represented in the ANCAT/EC2 inventory. The most significant omission of ATC data was the United States, for which data were unavailable for security reasons. Thus, only time table data were used for the United States; so nonscheduled U.S. domestic charters and other flights were not recorded. To compensate for this problem, fuel usage data were factored up by 10% (Gardner, 1998). ATC data accounted for half of the non-U.S. aircraft movements in the database. Military movements were estimated by allocating fuel and emissions to countries' boundaries from an analysis of the world's military fleet composition.

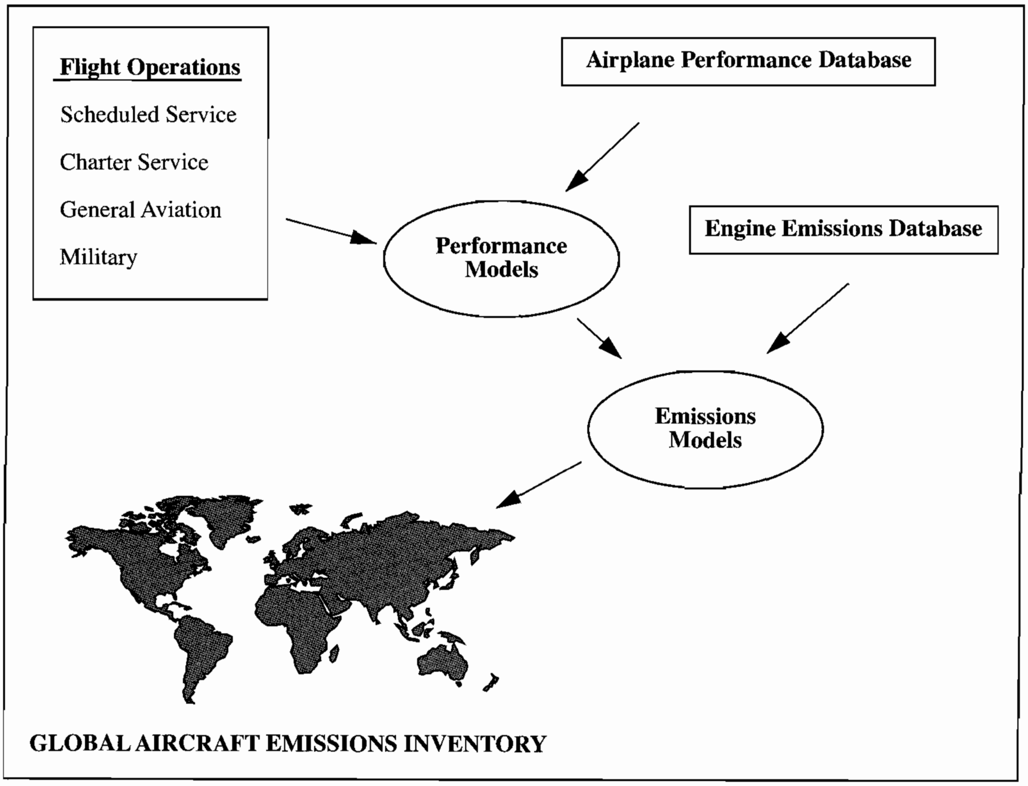


**Figure 9-5**: Aircraft emissions inventory calculation schematic.

The DLR inventory for 1991/92 (Schmitt and Brunner, 1997) used the ANCAT/EC2 civil movements database. Emissions inventories for 1986, 1989, and 1992 were based on scheduled air traffic only; a 4-D inventory with diurnal cycles for March 1992 was based on ABC data. ICAO data (ICAO, 1997b) were used for emissions inventories for international (only) scheduled air traffic in the years 1982 to 1992.

Calculation of fuel burned and emissions for aircraft differs between the three inventories. NASA used detailed manufacturers' proprietary performance information on each aircraft-engine combination and the flight profile shown in Figure 9-6. Emissions were calculated from the information in the ICAO Engine Exhaust Emissions Data Bank (ICAO, 1995), through the use of Boeing "Method 2" procedures (Baughcum *et al.*, 1996b, Appendix D), which allow extrapolation of sea-level data in the ICAO data bank to the operating altitudes and temperatures encountered throughout the aircraft flight profile.

The ANCAT/EC2 inventory used commercial software for flight and fuel profiling, along with Project Interactive Analysis and Optimization (PIANO), a parametric aircraft design model. The global civil fleet was modeled with a selection of 20 representative aircraft types. These representative aircraft were assumed to be fitted with generic engines typical of the technology and thrust requirements of each type. PIANO generated fuel profiles covering the entire flight cycle, including steps in cruise for each aircraft. Fuel use during ground operations was estimated from ICAO certification timings (ICAO, 1993).

The DLR inventory used airline data and an in-house flight and fuel profile model (Deidewig *et al.*, 1996). The DLR approach also used different aircraft/engine combinations from those utilized by ANCAT. The aircraft mission was simulated by using a simplified flight modeling code as point-to-point missions with no step cruise. Although the climb was calculated in iterative steps, the cruise segment was treated as one section, applying the Breguet formula to calculate the cruise fuel. Descent was assumed to be a gliding path with minimum engine load; no separate approach procedure was used. A thermodynamic model for design and off-design operation of a two-shaft fan engine was applied. Constant efficiencies and constant relative pressure losses for main engine components were assumed for simplicity.

The ANCAT/EC2 and DLR inventories calculated $NO_x$ emissions from the fuel using the DLR fuel flow method. This method has been tested and correlated with information from airlines, flight measurements, and altitude chamber measurements (Deidewig *et al.*, 1996; Schulte *et al.*, 1997).

### 9.3.2. *NASA, ANCAT/EC2, and DLR 2015 Emissions Forecasts*

The first NASA subsonic aircraft emissions inventory for 2015 was created as part of an assessment of the effects of a future HSCT (Baughcum *et al.*, 1994); it has now been superseded by a new study (Baughcum *et al.*, 1998; Mortlock and Van Alstyne, 1998) that includes new emissions technology assumptions and more detailed fleet mix and route system calculations. The NASA 2015 forecast inventory was calculated using methods similar to those used for NASA's historical and present-day inventories. Separate forecasts were created for scheduled operations (flights shown in the OAG database), charter operations, cargo operations, domestic operations in the FSU and China, military operations, and general aviation.

The forecast for scheduled traffic was based on the 1996 Boeing Current Market Outlook (Boeing, 1996), which projects separate traffic growth rates by region. Growth in worldwide demand for air travel was expected to average about 5% per

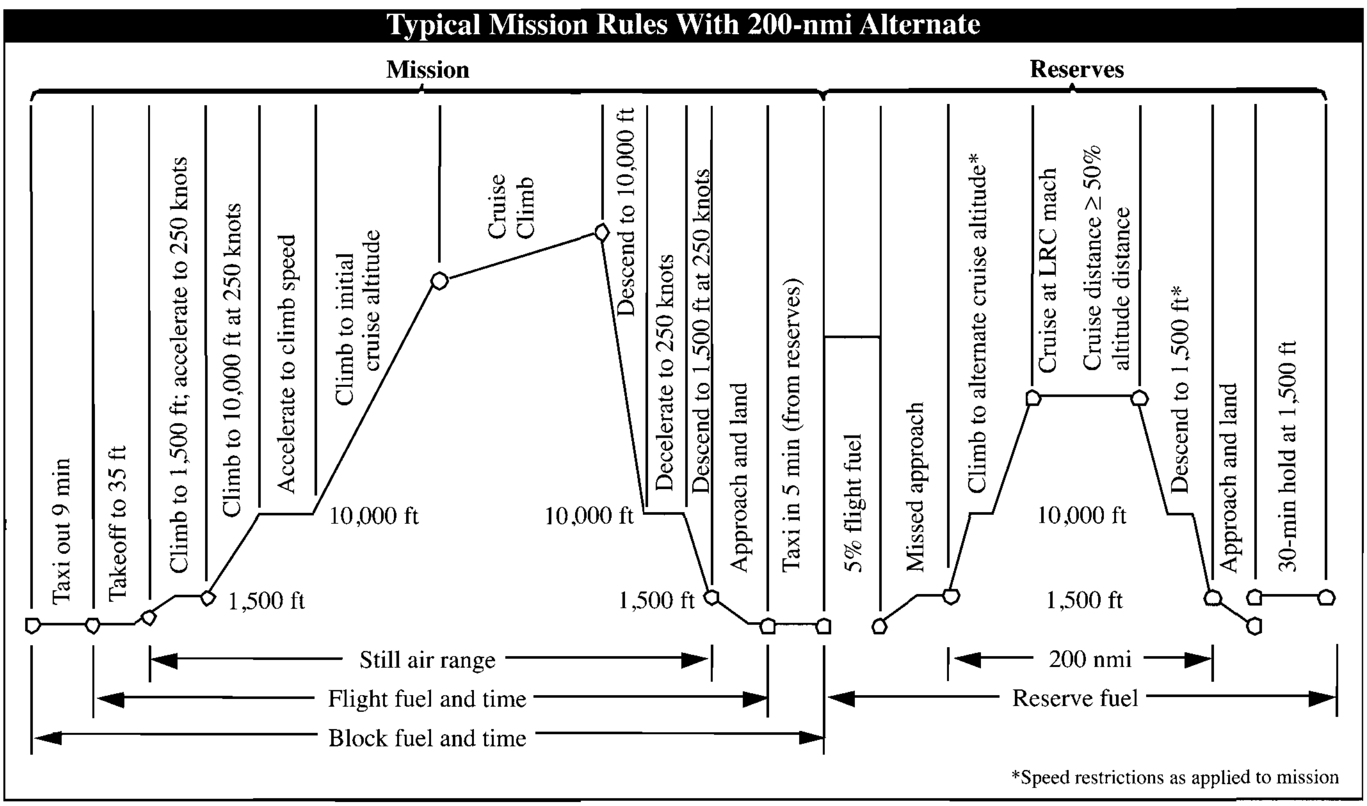


**Figure 9-6**: Scheduled aircraft mission profile.

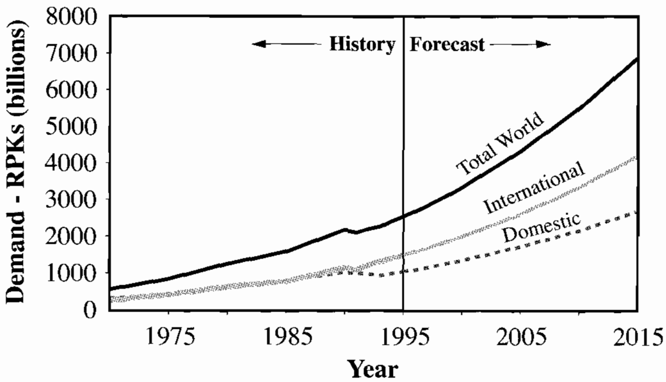


**Figure 9-7**: Passenger traffic demand growth to 2015.

year to the year 2015, with international travel growing at a slightly faster rate than domestic travel (Figure 9-7). By 2015, demand for air travel is projected to be 2.5 times greater than in 1996.

The total projected demand for scheduled air travel in the year 2015 was assigned to actual aircraft on a projected city-pair schedule derived from the schedules for 1995 published in the OAG. Individual city-pair service schedules for 1995 within each of the traffic flow regions were grown to 2015 by using the consolidated regional growth rate applicable for that region. Aircraft types were assigned to routes by using a market share forecast model. The turboprop market (for which there was no detailed forecast) was projected for 2015 by assuming that city pairs not served by the smallest turbojet category (50–90 seats) after demand growth to 2015 will continue to be served by small, medium, or large turboprops.

The result of the fleet assignment task was a detailed city-pair flight schedule by aircraft type required to satisfy forecast scheduled passenger demand in 2015. This schedule was used to calculate the 3-D emissions inventory for scheduled passenger service. Simplifying assumptions were the same as those used in calculating the historical and present-day inventories.

Projections of engine and aircraft technology levels for the 2015 scheduled fleet with regard to fuel efficiency and $NO_x$ emissions were made by assuming a continuation of present trends. In general, engines in the 2015 scheduled fleet represent the state-of-the-art in engine technology available either in production or in the final stages of development at the time the assignments were made (1997). These engines include low-emissions derivatives of previously existing engines. It is unlikely that any radical changes in airframe or engine design—even if such designs were acceptable—would have much of an effect on the 2015 fleet, given the time required to bring new designs into service. The combined effects of 2015 fleet mix and technology projections on the $NO_x$ technology level of the projected 2015 fleet appear in Figure 9-8, which shows the percentage of total fleet fuel burned by aircraft having landing/take-off cycle (LTO) emissions at a given level relative to the CAEP/2 $NO_x$ limit. (CAEP is chartered to propose worldwide certification standards for aircraft emissions and noise. The CAEP/2 designation refers to emissions certification standards adopted at the second meeting of the CAEP in December 1991.) Much more of the fleet consists of low-$NO_x$ aircraft-engine combinations in 2015, with ~70% of fuel burned in engines with $NO_x$ emission levels between 20 and 40% below the CAEP/2 certification limit.

DTI has developed a traffic and fleet forecast model for civil aviation, which was adapted under the direction of ANCAT and EIDG to produce an estimate of fuel burned and $NO_x$ emitted by civil aviation for the forecast year of 2015 (Gardner, 1998). Fuel and $NO_x$ growth factors—base to forecast—were calculated and applied to the ANCAT/EC2 city-pair gridded 1992 base year inventory to produce a gridded 2015 forecast.

DTI's top-down regional traffic demand forecasting model has a horizon of 25 years. Traffic coverage in the model includes all scheduled civil operations but excludes the former Soviet Union, Eastern Europe, freight, military, non-European charter traffic, business jets, and general aviation. Factors were developed to account for these traffic sectors in the forecast. The traffic forecast assumes a relationship between traffic [available seat-kilometers (ASK)] and GDP growth, and is assessed on a regional and flow basis (i.e., traffic flow between specific regions). The relationship is modified by assumptions on airline yields—a surrogate for fares price—and by a market maturity term that modifies demand as a function of time. Future fleets are estimated from traffic forecasts in terms of size and composition.

The concept of "traffic efficiency" was used to estimate fuel consumption from traffic values. Traffic efficiency is defined as the amount of traffic or capacity (ASK) per unit of fuel consumed. Aircraft manufacturers' traffic efficiency data for current aircraft types and projections for future aircraft types were used to develop efficiency trends for the eight categories of generic aircraft adopted for forecasting purposes, over a range of flight sector lengths. This approach permitted estimation of fuel consumption on the basis of regional and global traffic forecasts.

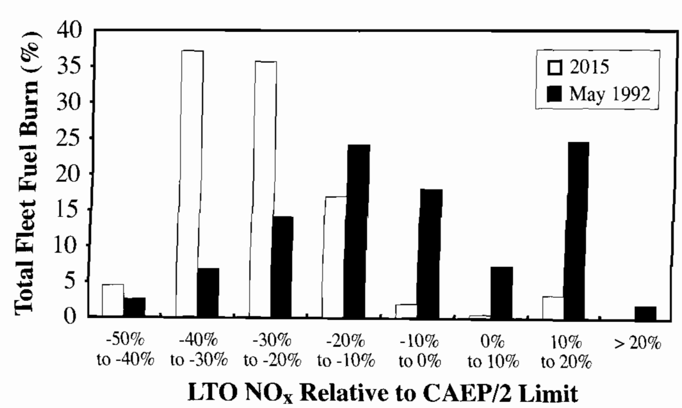


**Figure 9-8**: Percentage of total scheduled fleet fuel burned by aircraft in specific LTO $NO_x$ emissions categories for May 1992 (Baughcum *et al.*, 1996b) and the year 2015 projection (Baughcum *et al.*, 1998).

Average efficiency figures were also calculated for the eight generic aircraft types in the 1992 base year fleet; a fleet average value of about 24.0 seat-km per liter was found. This figure compares well with those in Greene (1992) and Balashov and Smith (1992) for the years 1989 and 1990, respectively, which gave traffic efficiencies of 20.5 seat-km per liter.

Greene (1992) and Balashov and Smith (1992) forecast an annual improvement in commercial air fleet fuel efficiency (see Table 9-2). These efficiencies include improvements arising from the introduction of new aircraft into the fleet and changes to operating conditions and passenger management. For the DTI work, the Greene (1992) forecasts were used to 2010. Annual improvements in fuel efficiency was assumed to decrease to 1% per year beyond 2010.

Using this efficiency trend, traffic efficiencies were calculated for the future aircraft fleet. The base year fleet average was estimated to increase to 31.8 seat-km per liter by 2015.

The same trends in fuel efficiency were applied to all size and technology classes. This approach represents a simplification because improvement figures are really a fleet average and would be influenced strongly by the rate of introduction of new aircraft. Given the much smaller contribution of older aircraft to global traffic performance, however, this factor will be only a second-order effect.

The emission performance of the forecast fleet was determined in part by the assumed response of the engine manufacturing industry to an assumed regulatory scenario. An emissions certification stringency regime was proposed for the forecast period, and compliance with the tighter limits was achieved by modifying the emissions performance of engines as they became noncompliant. This calculation was assessed from a base year engine fleet, comprising engines typical of and representing those found in the fleet (and compatible with the aircraft generic types described above). Performance improvements were applied only to new fleet entrants and were appropriate for staged and ultra-low $NO_x$ control technology in some cases.

This process results in an estimate of fuel burn and $NO_x$ emissions for the base year and forecast fleet using the same methodology; 1992–2015 fuel and $NO_x$ growth factors are thereby calculated. The growth factors were applied to the ANCAT/EC2 base year gridded fuel and $NO_x$ estimates to provide a 2015 gridded forecast.

The methods used to project civil aviation traffic demand for the DLR 2015 inventory were based on regional growth factors calculated by DTI. Thus, the DLR 2015 forecast differs from the ANCAT/EC2 forecast only in that the base year inventory is slightly different because of the different fuel and profiling methodology and the aircraft generic types. Thus, in the comparison of results, ANCAT and DLR 2015 forecasts are not assumed to be different because the DLR forecast is essentially an application of the DTI/ANCAT forecast.

***Table 9-2**: Future trends in fuel efficiency improvement.*

| Time Period | Fuel Efficiency Improvement |
|---|---|
| 1993–2000 | 1.3% $yr^{-1}$ |
| 2000–2010 | 1.3% $yr^{-1}$ |
| 2010–2015 (extrapolation) | 1.0% $yr^{-1}$ |

### *9.3.3. Other Emissions Inventories*

Studies of atmospheric effects of aviation were conducted using the global inventory of McInnes and Walker (1992) and emissions data sets produced by the Dutch Institute of Public Health and Environmental Protection for 1990, 2003, and 2015 (Olivier, 1995) based on the McInnes and Walker (1992) data. Other emissions estimates are predominantly made on a national level (e.g., in Austria and Sweden).

The Dutch Aviation Emissions and Evaluation of Reduction Options (AERO) Project was initiated in 1994 by the Dutch Civil Aviation Department to estimate economic and environmental impacts of possible measures to reduce aviation emissions (see Chapter 10). Within this project, the flights and emissions model (FLEM) was developed for the calculation of worldwide fuel use and emissions per grid cell (ten Have and de Witte, 1997). The base year traffic movements database is a combination of data from ANCAT/EC2, International Air Transport Association, the ABC schedule, ICAO, and the U.S. Department of Transportation (DOT). Global volumes for aircraft kilometer, fuel consumption, and emissions ($CO_2$, $NO_x$) resulting from computations of the AERO modeling system for civil aviation for base year 1992 and forecast for 2015 (called FPC-2015 scenario) are listed in Table 9-3. Further details appear in Pulles (1998).

### *9.3.4. Comparisons of Present-Day and 2015 Forecast Emissions Inventories (NASA, ANCAT/EC2, and DLR)*

Table 9-4 lists the totals for calculated fuel burned and emissions from the NASA, ANCAT, and DLR inventories for 1976, 1984, 1992, and 2015. Because these inventories consisted of 3-D

***Table 9-3**: Results from AERO modeling analysis.**

| | 1992 | 2015 | Annual Change |
|---|---|---|---|
| Aircraft kilometers (km $yr^{-1}$) | 20.7 x $10^9$ | 49.6 x $10^9$ | 3.9% |
| Fuel consumption (Tg $yr^{-1}$) | 144 | 278 | 2.9% |
| $CO_2$ emissions (Tg $yr^{-1}$) | 453 | 877 | 2.9% |
| $NO_x$ emissions (Tg $yr^{-1}$) | 1.84 | 3.86 | 3.3% |

*AERO results for base and datum (FPC-2015 scenario).

***Table 9-4**: Calculated fuel and emissions from NASA, ANCAT, and DLR inventories.*

| | NASA 1976 | NASA 1984 | NASA 1992 | ANCAT 1992 | DLR 1992 | NASA 2015 | ANCAT 2015 | DLR 2015 |
|---|---|---|---|---|---|---|---|---|
| *Calculated Fuel Burned (Tg)* | | | | | | | | |
| Scheduled | 45.83 | 64.17 | 94.84 | | | 252.73 | | |
| Charter | 8.47 | 9.34 | 6.57 | | | 13.50 | | |
| FSU/China | 6.05 | 7.43 | 8.77 | | | 15.79 | | |
| General Aviation | 4.04 | 5.62 | 3.68 | | | 6.03 | | |
| Civil Subtotal | 64.38 | 86.56 | 113.85 | 114.20 | 112.24 | 288.05 | 272.32 | 270.50 |
| Military | 35.66 | 29.76 | 25.55 | 17.08 | 17.10 | 20.59 | 14.54 | 14.50 |
| Global Total | 100.04 | 116.31 | 139.41 | 131.3 | 129.34 | 308.64 | 287.86 | 285.00 |
| *Calculated $CO_2$ Emissions (Tg C)* | | | | | | | | |
| Scheduled | 39.41 | 55.18 | 81.56 | | | 217.35 | | |
| Charter | 7.28 | 8.03 | 5.65 | | | 11.61 | | |
| FSU/China | 5.20 | 6.39 | 7.54 | | | 13.58 | | |
| General Aviation | 3.47 | 4.83 | 3.16 | | | 5.18 | | |
| Civil Subtotal | 55.36 | 74.44 | 97.91 | 98.22 | 96.52 | 247.72 | 234.21 | 232.63 |
| Military | 30.67 | 25.59 | 21.98 | 14.68 | 14.71 | 17.71 | 12.50 | 12.47 |
| Global Total | 86.03 | 100.03 | 119.89 | 112.92 | 111.23 | 265.43 | 246.71 | 245.10 |
| *Calculated $NO_x$ Emission (Tg as $NO_2$)* | | | | | | | | |
| Scheduled | 0.50 | 0.79 | 1.23 | | | 3.57 | | |
| Charter | 0.09 | 0.11 | 0.09 | | | 0.19 | | |
| FSU/China | 0.04 | 0.06 | 0.06 | | | 0.12 | | |
| General Aviation | 0.06 | 0.07 | 0.05 | | | 0.07 | | |
| Civil Subtotal | 0.70 | 1.02 | 1.44 | 1.60 | 1.60 | 3.95 | 3.37 | 3.41 |
| Military | 0.28 | 0.25 | 0.23 | 0.20 | 0.20 | 0.18 | 0.16 | 0.16 |
| Global Total | 0.98 | 1.28 | 1.67 | 1.81 | 1.80 | 4.12 | 3.53 | 3.57 |
| *Calculated Fleet Average $NO_x$ Emission Index [g $NO_x$ (as $NO_2$) $kg^{-1}$ fuel burned]* | | | | | | | | |
| Scheduled | 10.9 | 12.3 | 13.0 | | | 14.1 | | |
| Charter | 10.8 | 11.3 | 13.3 | | | 13.8 | | |
| FSU/China | 7.4 | 7.4 | 7.4 | | | 7.4 | | |
| General Aviation | 14.5 | 12.6 | 14.4 | | | 11.3 | | |
| Civil Subtotal | 10.8 | 11.8 | 12.6 | 14.0 | 14.2 | 13.7 | 12.4 | 12.6 |
| Military | 8.0 | 8.5 | 8.9 | 11.9 | 11.8 | 8.7 | 10.7 | 10.8 |
| Global Total | 9.8 | 11.0 | 12.0 | 13.8 | 13.9 | 13.4 | 12.3 | 12.5 |

data sets, the differences in spatial distributions as well as totals are compared. The NASA inventories also included emissions of CO and HC, which are summarized in Table 9-5.

The NASA inventories include piston-powered aircraft in the general aviation fleet. This category of aircraft is excluded from the ANCAT and DLR inventories, but the contribution to total fuel burned from these aircraft is small (2.6% of fuel burned in 1992). Piston-powered aircraft are large contributors to CO and HC emissions relative to the amount of fuel they burn (39% of CO and 13% of HC emissions in 1992). This large relative contribution is reflected in the emissions indices of these two pollutants in the general aviation category.

A comparison of calculated global total values for fuel burned and $NO_x$ emissions from the NASA, ANCAT, and DLR inventories for 1992 and 2015 is shown in Figure 9-9. All three inventories for 1992 have approximately the same calculated values for total fuel burned in the civil air fleet; the difference in total fuel (7% maximum) arises almost entirely from different calculated contributions for military aviation operations, for which the ANCAT inventory calculates 33% lower fuel burned. Because military fuel is estimated to be between 13 and 18% of total fuel in 1992, the effect of this large difference in estimates between military sectors on the total is small. Use of the NASA inventories as a base is arbitrary and does not imply that differences from the NASA results are errors. Exclusion of turboprop operations from the ANCAT inventory results in about a 2% underestimate (if data from the NASA inventory are used).

Calculated values for total $NO_x$ emissions from the three inventories for 1992 are within 9% of each other. The ANCAT

***Table 9-5**: Emissions of CO and HC from NASA inventories.*

| | NASA 1976 | NASA 1984 | NASA 1992 | NASA 2015 |
|---|---|---|---|---|
| *Calculated CO Emissions (Tg)* | | | | |
| Scheduled | 0.41 | 0.41 | 0.50 | 1.12 |
| Charter | 0.03 | 0.04 | 0.02 | 0.05 |
| FSU/China | 0.10 | 0.12 | 0.15 | 0.26 |
| General Aviation | 0.73 | 0.75 | 0.62 | 0.60 |
| Civil Subtotal | 1.27 | 1.32 | 1.29 | 2.04 |
| Military | 0.43 | 0.35 | 0.29 | 0.23 |
| Global Total | 1.70 | 1.67 | 1.57 | 2.27 |
| *Calculated Fleet Average CO Emissions Index (g CO $kg^{-1}$ fuel burned)* | | | | |
| Scheduled | 8.9 | 6.3 | 5.3 | 4.5 |
| Charter | 4.0 | 4.0 | 3.7 | 3.9 |
| FSU/China | 16.6 | 16.6 | 16.6 | 16.6 |
| General Aviation | 180.1 | 133.0 | 167.6 | 99.4 |
| Civil Subtotal | 19.7 | 15.2 | 11.3 | 7.1 |
| Military | 12.0 | 11.9 | 11.2 | 11.3 |
| Global Total | 17.0 | 14.4 | 11.3 | 7.4 |
| *Calculated HC Emissions (Tg)* | | | | |
| Scheduled | 0.27 | 0.20 | 0.20 | 0.17 |
| Charter | 0.01 | 0.01 | 0.00 | 0.01 |
| FSU/China | 0.02 | 0.02 | 0.03 | 0.05 |
| General Aviation | 0.03 | 0.05 | 0.04 | 0.05 |
| Civil Subtotal | 0.33 | 0.28 | 0.26 | 0.28 |
| Military | 0.09 | 0.07 | 0.06 | 0.05 |
| Global Total | 0.42 | 0.35 | 0.32 | 0.33 |
| *Calculated Fleet Average HC Emissions Index (g HC $kg^{-1}$ fuel burned)* | | | | |
| Scheduled | 5.8 | 3.2 | 2.1 | 0.7 |
| Charter | 0.9 | 0.9 | 0.5 | 0.6 |
| FSU/China | 3.2 | 3.2 | 3.2 | 3.2 |
| General Aviation | 8.2 | 8.5 | 9.9 | 8.6 |
| Civil Subtotal | 5.1 | 3.3 | 2.3 | 1.0 |
| Military | 2.5 | 2.3 | 2.4 | 2.5 |
| Global Total | 4.2 | 3.0 | 2.3 | 1.1 |

and DLR values are higher than those from NASA—a result of a combination of differing fleet mixes, a different method of calculating $NO_x$ emissions, and the offsetting effects of civil and military calculations. This variation is also reflected in the calculated EI($NO_x$) for the fleet components: The ANCAT and DLR inventories have a total fleet emission index that is 15% higher than that of the NASA inventory.

Differences between inventory totals widen for the 2015 case, although total fuel burned is still within 8%. Total $NO_x$ emissions in the NASA 2015 forecast are almost 15% greater than those in the ANCAT forecast, a result of different assumptions about the direction of $NO_x$ reduction technology (the NASA assumptions result in an increase in $NO_x$ emissions index in the civil sector, whereas the ANCAT forecasts assume a reduction).

Other differences between the NASA, ANCAT, and DLR inventories relate to the distribution of calculated fuel burned and emissions, geographically (latitude and longitude) and with altitude. Although all three inventories place more than 90% of global fuel burned and emissions in the Northern Hemisphere, there are differences between inventories in the details of the distribution. Figure 9-10 shows the distribution of fuel burned as calculated in 1 month (May) of the 1992 NASA inventory. The most heavily trafficked areas are clearly visible (United States, Europe, North Atlantic, North Asia).

For geographical comparison purposes, data in the files of the NASA and ANCAT 1992 inventories were divided into 36 regions, defined by 60° spans of longitude and 20° spans of latitude. Figure 9-11 shows the differences between the ANCAT and NASA 1992 inventories with regard to geographical distribution.

The major differences between the NASA and ANCAT inventories (on a geographical basis) lie in the estimate of fuel burned and $NO_x$ emissions in the regions covering North America and Europe. The ANCAT inventory places 32% of total fuel burned and 30% of total $NO_x$ over North America, whereas the NASA inventory places 27% of fuel burned and 27% of $NO_x$ over that region. ANCAT places 16% of the fuel and 15% of the $NO_x$ over Europe, whereas the NASA inventory places 21% of the fuel and 19% of total $NO_x$ over that region. Part of this difference may be explained by the 10% scaling of U.S. traffic assumed by ANCAT as a method of approximating the U.S. charter market.

NASA and ANCAT fuel and $NO_x$ emissions projections for 2015 are similar to the respective 1992 inventories in that no new city pairs were used in the 2015 traffic projections. Growth rates from 1992 to 2015 vary with region, so the geographical distribution of emissions changes over time.

The altitudinal distributions of fuel burned in the present-day NASA, ANCAT, and DLR inventories are shown for civil aviation in Figure 9-12 and for military aviation in Figure 9-13. The civil aviation distributions are similar, with the NASA inventory showing more fuel burned at higher altitudes. The military distributions are quite different, with fuel burned in the NASA inventory concentrated at the higher altitudes and fuel burned in the ANCAT inventory at lower altitudes. This difference may be because of a higher proportion of transport operations in the NASA inventory. The altitudinal distribution of $NO_x$ emissions follows closely that of fuel burned. The three inventories show that more than 60% of the fuel burned and $NO_x$ emissions occur above 8 km, whereas a major fraction of CO and HC are emitted near the ground.

Although the three inventories show comparably low variations for total global monthly figures over the year, the seasonal dependency can be quite large for some regions (Figure 9-14). Operations in the North Atlantic and North Pacific show a clear yearly cycle, with a maximum in the northern summer and a minimum during winter. In contrast, Southern Hemisphere operations show little seasonal variation overall, with small peaks in February and November.

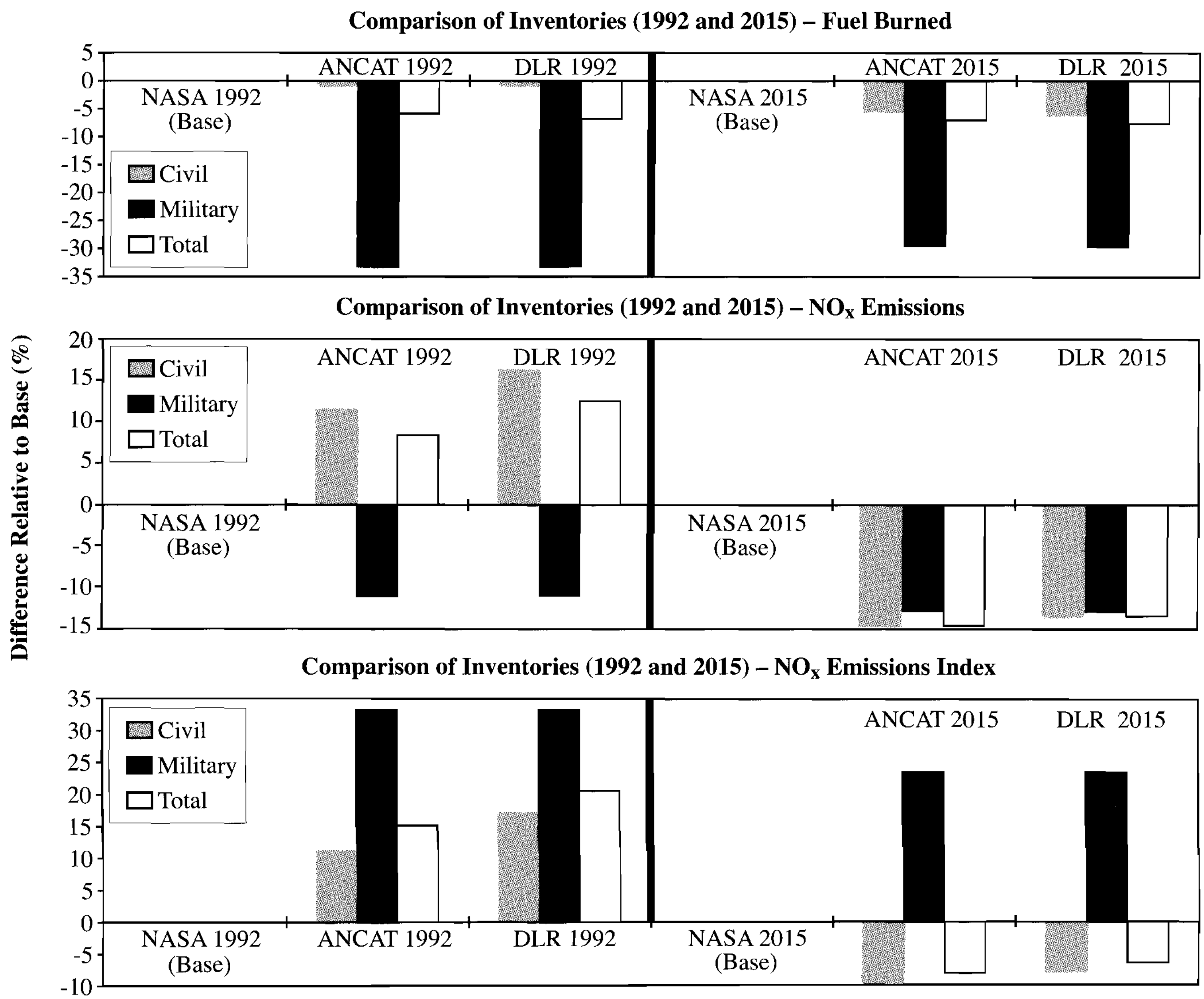


**Figure 9-9**: Comparison of inventories.

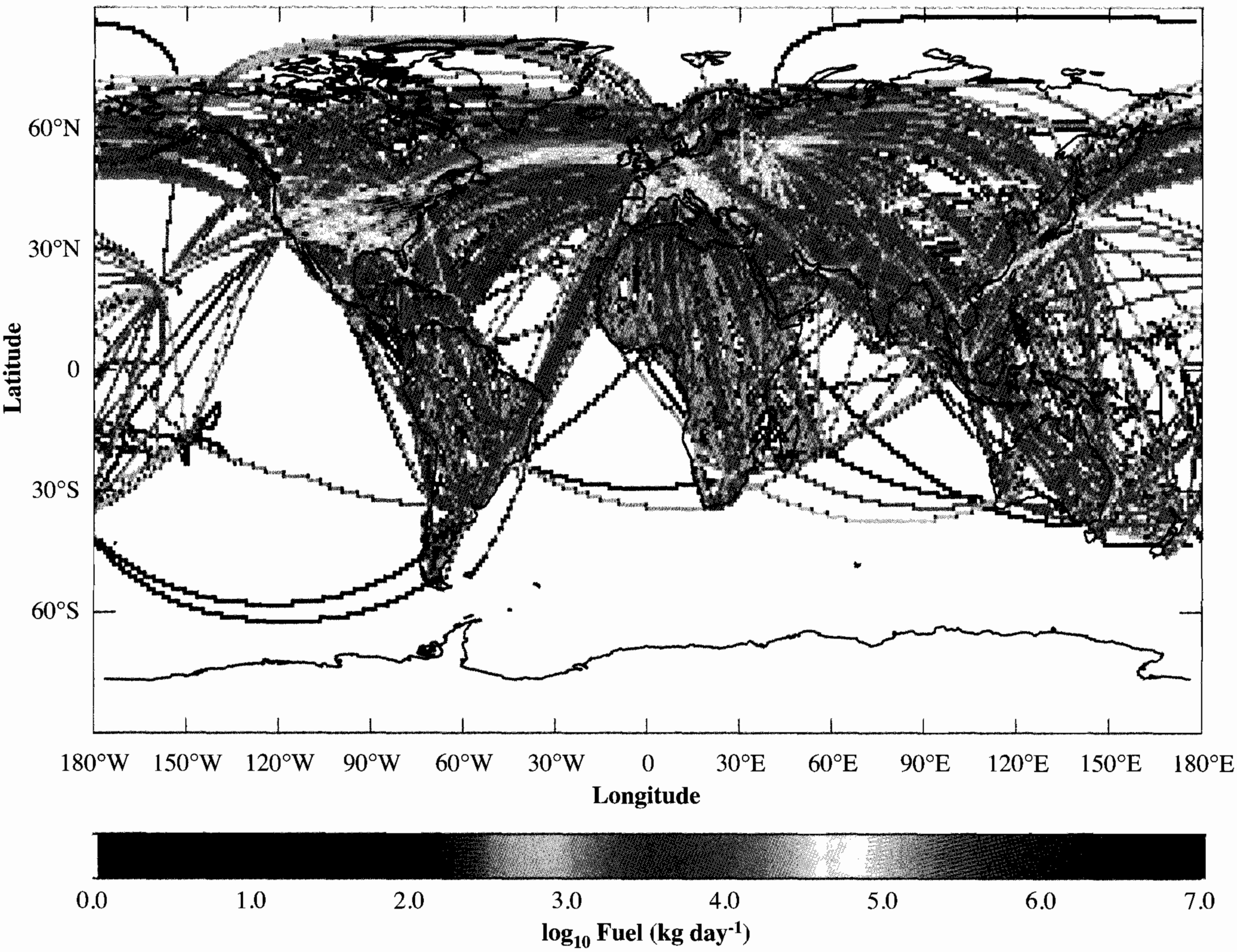


**Figure 9-10**: Geographical distribution of fuel burned by civil aviation (May 1992).

DLR has also examined longer trends in fuel burned and emissions for air traffic (Schmitt and Brunner, 1997). 3-D gridded inventories of fuel burned and emissions were calculated for 1982 through 1992 using ICAO statistics on annual values for international scheduled air traffic and ABC time table data of all scheduled air traffic for the same week of September in 1986, 1989, and 1992. Emissions inventories were produced for each of these data sets using the same methods as in the 1992 DLR inventory described above. These inventories concentrate on scheduled services because reasonably accurate calculations are possible for this segment of aviation. Because these data do not include non-scheduled flights, military traffic, general aviation, or former Soviet Union/China traffic, they are of limited use in global modeling studies. However, they do provide a consistent set of data to track the growth of the international and domestic scheduled sector. Table 9-6 gives the totals for the yearly inventories.

### *9.3.5. Error Analysis and Assessment of Inventories*

Simplifying assumptions used in creating all of the 3-D emissions inventories have introduced systematic errors in the calculations. An analysis of the effects of the simplifying assumptions on fuel burned used in the 1992 NASA inventory has been performed by Baughcum *et al.* (1996b). All of the assumptions have the effect of biasing the calculation toward an underestimate of fuel burned and emissions produced, as detailed in Table 9-7. The effects of the assumptions on the ANCAT and DLR inventories may be expected to be similar, because most of the simplifying assumptions used in those inventory calculations were similar to those in the NASA inventory.

The assumption of great-circle flight paths results in an underestimate of distance flown, although the practice of routing to take advantage of winds may result in lower fuel consumption than a great-circle path for a given flight. A study of international and domestic flights from German airports showed an average increase in flight distance of 10% for medium- and long-haul flights above 700 km, with larger deviations from great-circle routes for shorter flights (Schmitt and Brunner, 1997). Ground delays and in-flight holding at relatively low altitudes caused by congestion in the air traffic control system also adds to fuel consumption. Aircraft in service are subject to factors that may increase fuel consumption by up to 3% (e.g., engine deterioration, added weight from added systems, and increased surface roughness).

Factors that cause underestimates of fuel burned do not necessarily operate at the same time, so they are not additive. Sutkus *et al.* (1999) compared fuel burned for certain carriers

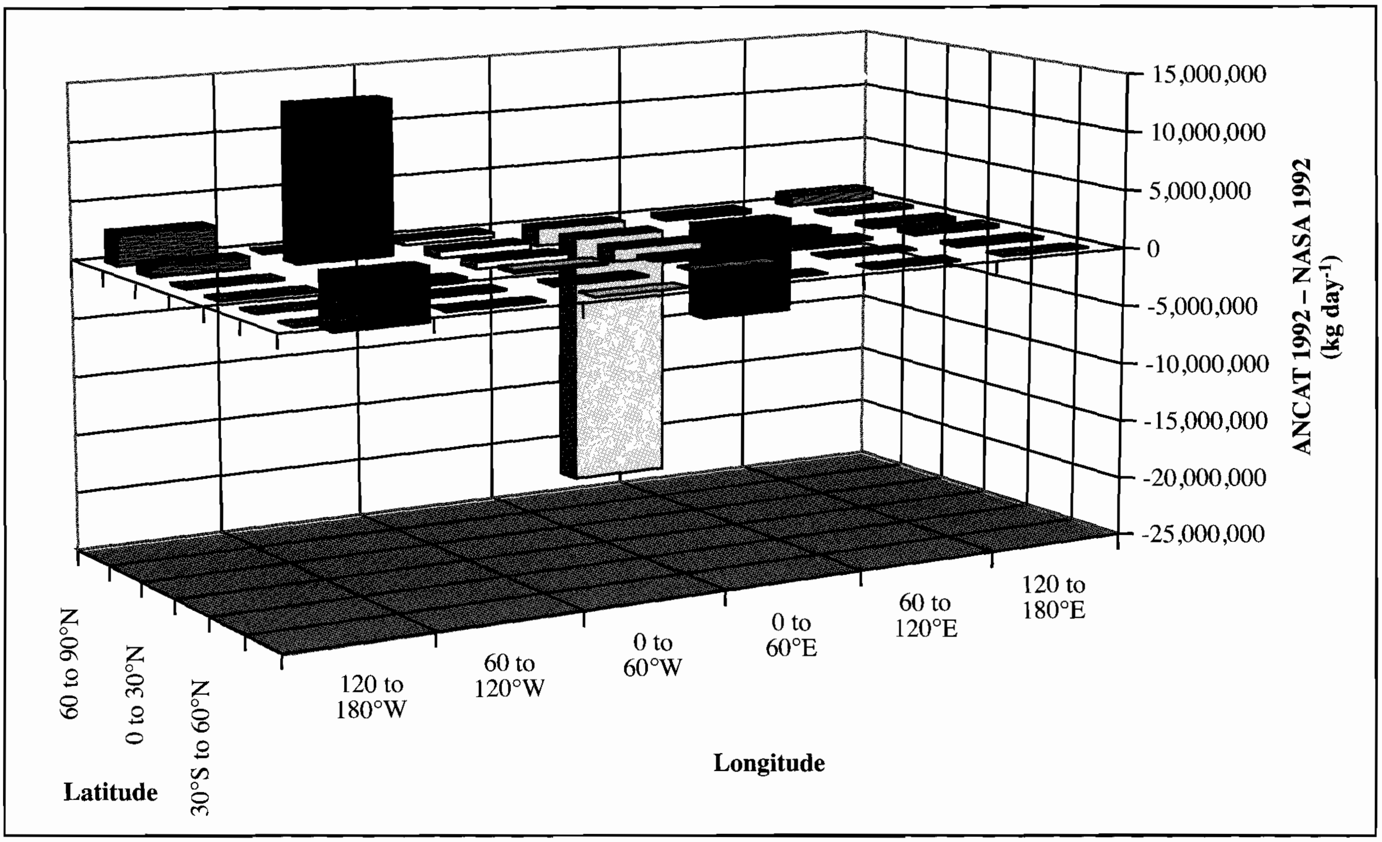


**Figure 9-11**: Differences in geographical distribution of fuel burned.

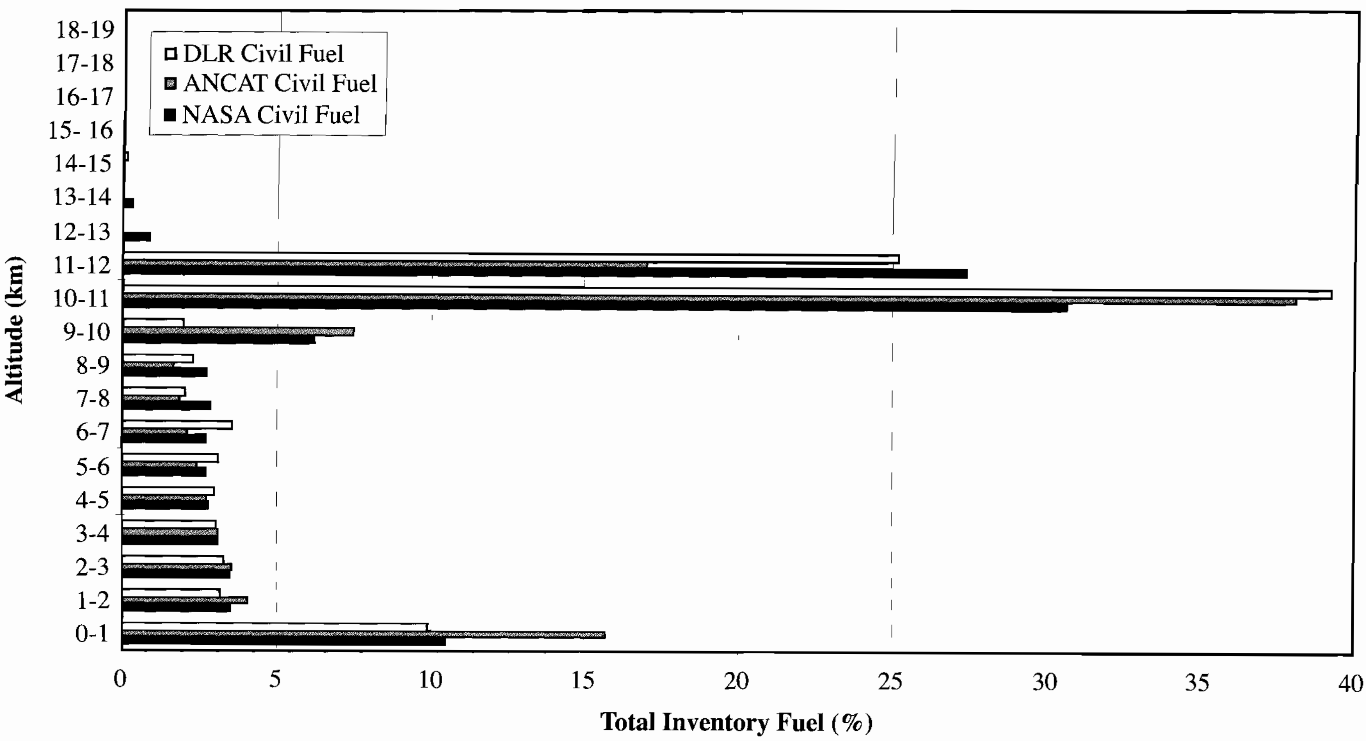


**Figure 9-12**: *Comparison of altitude distribution of 1992 inventories for civil aviation fuel burned.*

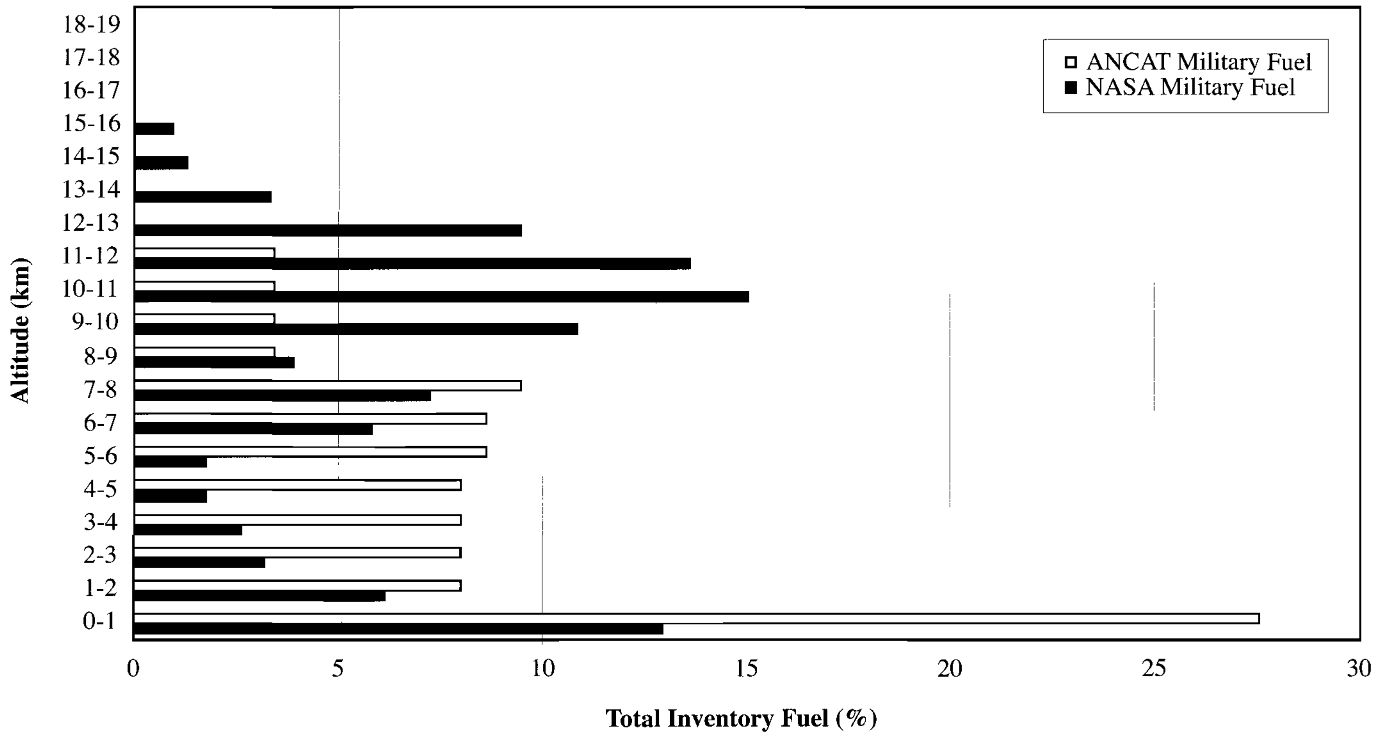


**Figure 9-13**: Comparison of altitude distribution of 1992 inventories for military aviation fuel burned.

and certain specific aircraft types reported to DOT by U.S. air carriers, with the value for fuel burned calculated for these carriers and aircraft types in the 1992 NASA inventory. The comparison shows that a combination of factors outlined above results in systematic underestimation of total fleet fuel burned by 15–20% for domestic operations. The assumptions in the foregoing analysis apply to the civil aviation fleet. An error analysis of the calculation of fuel burned and emissions from military operations is not possible, given the nature of the estimates used in the calculations.

The present-day inventories described above have reported global fuel consumption values for 1992 ranging from 129 to 139 Tg. However, reported aviation fuel production was somewhat larger, at 177 Tg (OECD, 1998a,b). Calculated fuel consumption therefore accounts for 73–80% of total fuel reported produced in 1992. Simplifying assumptions used in calculating the inventories probably account for most of the

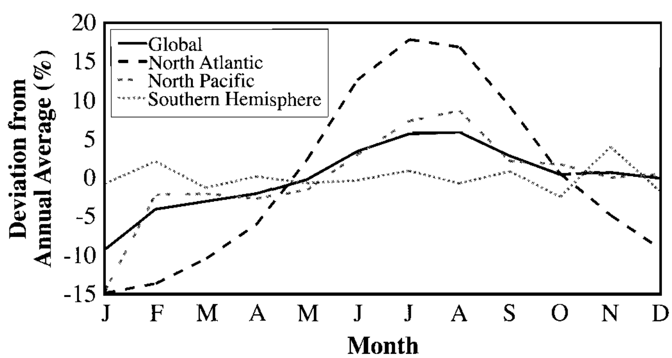


**Figure 9-14**: Regional seasonality of traffic.

difference. Reported fuel production values are not an ideal reference, however, because they do not necessarily represent fuel delivered to airports for use in aircraft. Jet fuel, in particular, is a fungible product; it can be reclassified and sold as kerosene or mixed with fuel oils or diesel fuel, depending on market requirements (e.g., when low freezing point fuel oil is needed in winter). Other distillate fuels from refineries may satisfy jet fuel requirements and could be purchased and used as jet fuel. As a consequence, reported jet fuel production data do not provide a rigorous upper or lower limit to jet fuel use. Fuel production data represent a compilation of reports of varying accuracy from many (not all) countries, whose overall accuracy has not been evaluated (Baughcum *et al.*, 1996b; Friedl, 1997).

OECD data on aviation fuel production from 1971 (the first year the data includes the former Soviet Union) to 1996 are shown in Figure 9-15. These data shown are the sum of OECD and non-OECD country production data. Reported data include production of aviation gasoline, naphtha-type jet fuel (mostly JP-4, used for military aircraft), and kerosene-type jet fuel (Jet A, the most common transport aircraft jet fuel). Also shown are calculated values of aviation fuel burned from the NASA, ANCAT, and DLR present-day inventories. (NASA values have been increased by 15% as a rough estimate of systemic underestimate of civil fuel burned.)

Aviation gasoline has declined as a percentage of total aviation fuel—from 4% of production in 1971, to just over 1% in 1995. Production of naphtha-type jet fuel reached just over 10% of total fuel in 1983, but has since declined to less than 1% as military aviation has phased out its use in favor of kerosene-type fuels. Prior to 1978, production of naphtha-type fuel was

***Table 9-6****: Fuel burned and emissions from scheduled air traffic, 1982–92 (DLR).*

| Year | Fuel [Int'l] (Tg) | $NO_x$ [Int'l] (Tg) | CO [Int'l] (Tg) | HC [Int'l] (Tg) | Fuel [Total] (Tg) | $NO_x$ [Total] (Tg) | CO [Total] (Tg) | HC [Total] (Tg) |
|---|---|---|---|---|---|---|---|---|
| 1982 | 19.2 | 0.31 | 0.05 | 0.02 | | | | |
| 1983 | 20.9 | 0.35 | 0.06 | 0.02 | | | | |
| 1984 | 24.7 | 0.41 | 0.06 | 0.03 | | | | |
| 1985 | 24.9 | 0.41 | 0.06 | 0.02 | | | | |
| 1986 | 26.7 | 0.44 | 0.07 | 0.03 | 72.2 | 1.03 | 0.24 | 0.10 |
| 1987 | 30.0 | 0.51 | 0.08 | 0.03 | | | | |
| 1988 | 32.6 | 0.55 | 0.09 | 0.03 | | | | |
| 1989 | 35.8 | 0.61 | 0.10 | 0.03 | 76.5 | 1.14 | 0.27 | 0.09 |
| 1990 | 37.2 | 0.62 | 0.11 | 0.04 | | | | |
| 1991 | 36.3 | 0.59 | 0.11 | 0.04 | | | | |
| 1992 | 39.3 | 0.62 | 0.10 | 0.03 | 93.0 | 1.31 | 0.34 | 0.10 |

***Table 9-7****: Analysis of the underestimate of fuel burned caused by simplifying assumptions (Baughcum et al., 1996b).*

| Changes to Simplifying Assumptions | Maximum % Fuel Burned Increase |
|---|---|
| No winds to actual winds | 2.6 (Autumn winds, North Pacific route) |
| Standard temperatures to actual temperatures | 0.7 (Summer temperature, North Pacific route) |
| Combined wind and temperature effects | 3.1 (Autumn winds, ISA+5°C temperature, North Pacific) |
| Payload: increase load factor to 75% | 0.8 (747-400, North Pacific) |
| Payload: increase load factor to 75% | 2.5 (737-300, Los Angeles–San Francisco) |
| Payload: volume limited cargo | 7.7 (747-400, North Pacific) |
| No fuel tankering to actual practice | 4.0 (737-300, Los Angeles–San Francisco, four leg mission) |

not reported as a separate item in the OECD database; it was included in the kerosene-type production data.

The three inventories are in good agreement; given the different approaches and data sources used, the inventory results (particularly for the present day) are remarkably consistent. Assumptions regarding the state of $NO_x$ reduction technology in 2015 cause the biggest difference in the results of the three forecasts. The 1992 and 2015 inventories of NASA, ANCAT, and DLR are all suitable for calculating the effects of aircraft emissions on the atmosphere, taking account of differences in the details of the inventories and systematic underestimates examined above. To correct for the systematic underestimation of fuel burned in the inventories when calculating the effects of aviation $CO_2$ emissions, fuel burned values for 1992 should be increased by 15% and those for 2015 should be increased by 5%, based on the assumption that inefficiencies in the air traffic control system responsible for extra fuel burned will be much reduced by 2015. A summary of the results from these inventories is given in Table 9-8. The DLR "trend" inventories (1982–92) include only a portion of total aviation operations (scheduled international service for all years and total scheduled service in 1986, 1989, and 1992); as such, they are valuable for historical growth analysis and for comparisons with the NASA and ANCAT/EC2 scheduled traffic segments.

## 9.4. Long-Term Emissions Scenarios

Long-term projections to the year 2050 producing 3-D emissions data have been made by the Forecasting and Economic Analysis Subgroup of CAEP, using the NASA studies as a base (CAEP/4-FESG, 1998), and by DTI using the ANCAT studies as a base (Newton and Falk, 1997). Long-term projections of total demand, fuel consumption, and emissions (but not providing 3-D data) have also been made by EDF (Vedantham and Oppenheimer, 1994, 1998), WWF (Barrett, 1994), and MIT (Schafer and Victor, 1997).

Predictions of traffic demand and resulting emissions beyond 2015 become increasingly uncertain because the probability

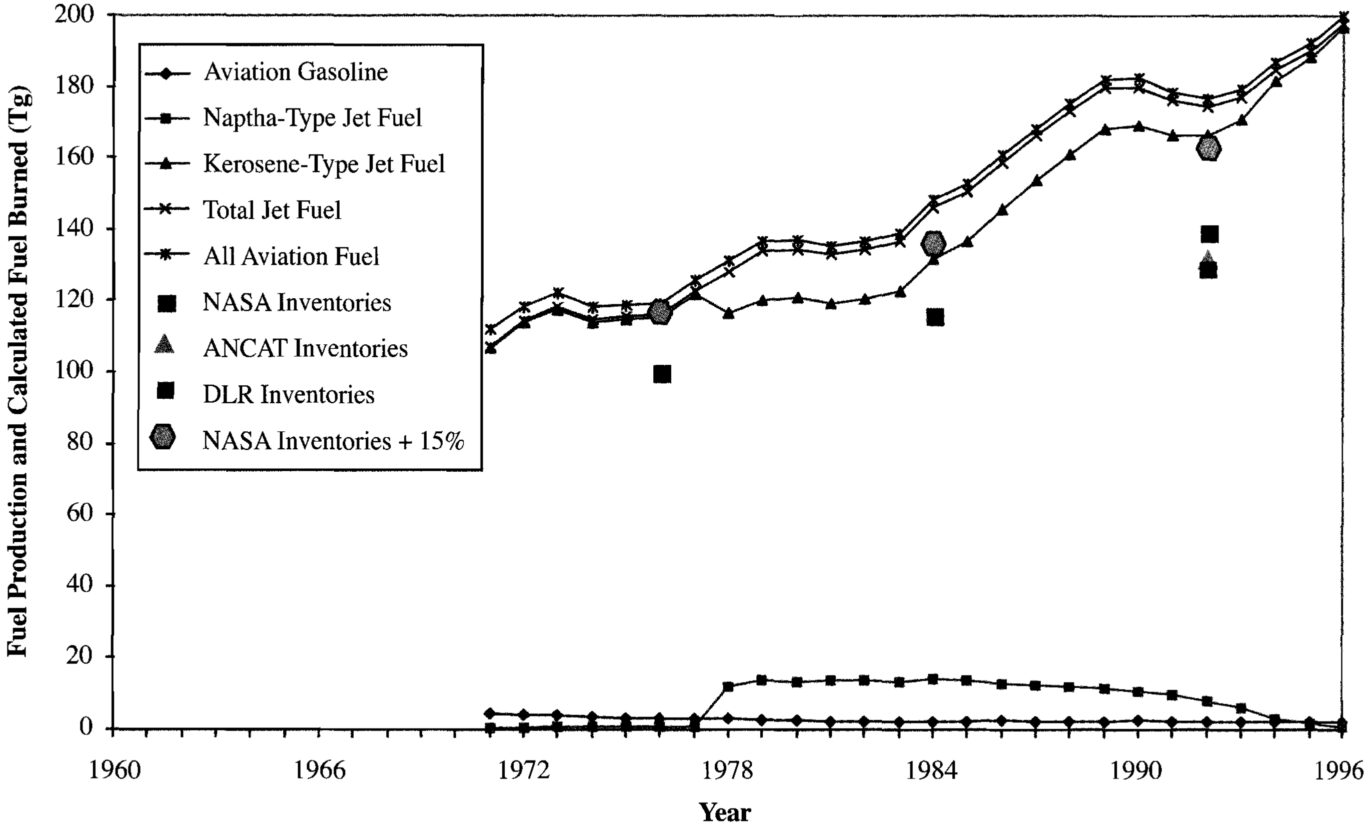


**Figure 9-15**: Comparison of calculated fuel burned by aviation with reported production.

for unforeseeable major changes in key factors influencing the results steadily increases. The best approach for insight into the evolution of long-term futures is the application of scenarios. A scenario is simply a set of assumptions devised to reflect the possible development of a particular situation over time. These assumptions are used as inputs to a model that describes the manner in which an activity might develop over time. A range of possible futures can be described by a set of independent scenarios. The results of the scenario are difficult to judge in terms of confidence level: They are simply the outcome of input assumptions. However, scenarios can be objectively judged as implausible by showing that their assumptions or outcomes conflict with industry trends or with invariant rules and laws that might reasonably be expected to remain unchanged during the scenario time period or by revealing internal inconsistencies or incompatibilities with other dominating external developments. Investigation of the consequences and implications of scenarios can be used to support a subjective assessment regarding which of the remaining possible scenarios might be more plausible than others.

### *9.4.1. FESG 2050 Scenarios*

#### *9.4.1.1. Development of Traffic Projection Model*

In developing long-term traffic scenarios, various models of traffic demand were considered (CAEP/4-FESG, 1998), particularly

***Table 9-8**: Summary comparison of historical, present-day, and 2015 forecast 3-D emissions inventories.*

| Inventory Year | Inventory Source | Calculated Fuel Burned (Tg) | Calculated $CO_2$ (as C) (Tg) | Calculated $NO_x$ (as $NO_2$) (Tg) | Calculated Fleet EI($NO_x$) (g $NO_2$ $kg^{-1}$ fuel) |
|---|---|---|---|---|---|
| 1976 | NASA | 100.0 | 86.0 | 1.0 | 9.8 |
| 1984 | NASA | 116.3 | 100.0 | 1.3 | 11.0 |
| 1992 | NASA | 139.4 | 119.9 | 1.7 | 12.0 |
| 1992 | ANCAT | 131.2 | 112.9 | 1.8 | 13.8 |
| 1992 | DLR | 129.3 | 111.2 | 1.8 | 13.9 |
| 2015 | NASA | 308.6 | 265.4 | 4.1 | 13.4 |
| 2015 | ANCAT | 287.1 | 246.9 | 3.5 | 12.3 |
| 2015 | DLR | 285.0 | 245.1 | 3.6 | 12.5 |

those incorporating a market maturity concept. Under this concept, historical traffic growth rates in excess of economic growth are considered unlikely to continue indefinitely, and traffic growth will eventually approach a rate equal to GDP growth as the various global markets approached maturity. Based on this assumption, a single global model of traffic demand per unit of GDP was developed, based on a logistics growth curve function:

$$\frac{RPK}{GDP} = \left( \frac{26.24}{1 + 9.04 \exp(-.073t)} \right)$$

t = time
RPK = revenue passenger-km
GDP = gross domestic product

The parameters in the model equation were estimated from historic values of RPK/GDP for the period 1960 through 1995. No constraints were imposed on the values the parameters could take. Further details of the modeling process appear in CAEP/4-FESG (1998). Table 9-9 lists the GDP growth assumptions used in developing these scenarios (Leggett *et al.*, 1992). The key assumptions of this approach follow:

- The world can be treated as a single, gradually maturing aviation market that is the sum of regional markets at various stages of maturity.
- Historical values of world demand and GDP over time provide sufficient information about the stage of development of the industry to provide reliable estimates of market maturity.
- Business and personal travel sectors can be combined.
- Global traffic growth is driven primarily by global GDP; as markets mature, overall passenger growth rates will eventually grow in line with GDP growth.
- Fuel will be available, and fuel prices will not increase greatly relative to other costs.
- Whatever aviation technological or regulatory changes occur, they will have no significant impact on ticket prices, demand, or service availability.
- Infrastructure will be sufficient to handle demand.
- There will be no significant impacts from other travel modes (e.g., high-speed rail) or alternative technologies (e.g., telecommunications).

Perhaps the most critical assumption of this methodology was that historical global traffic totals contained sufficient information about the maturity of the industry as a whole to provide a

***Table 9-9**: Summary of IPCC GDP scenarios used in FESG model.*

| Scenario | Average Annual Global GDP Growth Rate 1990–2025 | 1990–2100 |
|---|---|---|
| IS92a | 2.9% | 2.3% |
| IS92c | 2.0% | 1.2% |
| IS92e | 3.5% | 3.0% |

reasonable basis upon which long-term aviation trends could be projected. There is a question of whether the signals of recent years (i.e., that overall traffic growth is slowing) are sufficiently robust to provide a reliable indication of future long-term growth. A related concern is that historical world traffic totals are dominated by OECD experience, thus may not adequately capture the potential for growth in other, less-developed regions (CAEP/4-FESG, 1998). To a large extent, the FESG scenarios for 2050 reflect assumptions of no fundamental change in overall revenue/cost structure trends of the aviation industry and no fundamental changes in the trends in technology or society. They also assume that the growth of air traffic demand will not be significantly constrained by other limiting factors. Sections 9.6.5 and 9.6.6 examine the availability of infrastructure and fuel with regard to the plausibility of all of the long-term scenario projections.

Growth rates from the model were applied to 1995 reported world traffic demand (Boeing, 1996)—together with GDP growth rates from the IPCC IS92a, IS92e, and IS92c scenarios—to produce FESG base case (Fa), high (Fe), and low (Fc) scenarios of scheduled traffic demand. The high case (Fe) was adjusted slightly to match the NASA traffic forecast for 2015 on which the NASA 2015 emission inventory was based. The basis for the NASA 2015 traffic forecasts were GDP forecasts that were similar to the IS92e GDP scenario (Boeing, 1996). The resulting traffic demand and average growth rate for the three 2050 scenarios are illustrated in Figures 9-16 and 9-17 and listed in Table 9-10. The traffic demand scenarios have

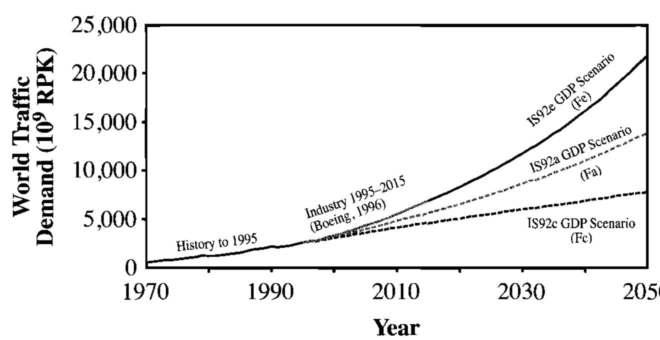


**Figure 9-16**: ICAO/FESG traffic demand scenarios to 2050 (based on IPCC IS92a, IS92c, and IS92e).

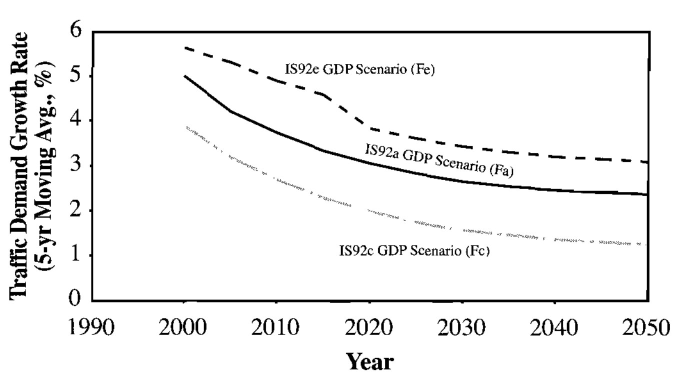


**Figure 9-17**: Average traffic growth rates from FESG model.

***Table 9-10**: Traffic projections and 5-year average growth rates from FESG (CAEP/4 – FESG Report 4, 1998).*

| Year | Fa Demand ($10^9$ RPK) | Fa Growth Rate (%) | Fc Demand ($10^9$ RPK) | Fc Growth Rate (%) | Fe Demand ($10^9$ RPK) | Fe Growth Rate (%) |
|---|---|---|---|---|---|---|
| 1995 | 2,536.6[a] | | 2,536.6[a] | | 2,536.6[a] | |
| 2000 | 3,238.0 | 5.0 | 3,068.8 | 3.9 | 3,336.1 | 5.6 |
| 2005 | 3,981.4 | 4.2 | 3,591.9 | 3.2 | 4,322.4 | 5.3 |
| 2010 | 4,782.6 | 3.7 | 4,103.0 | 2.7 | 5,491.7 | 4.9 |
| 2015 | 5,638.6 | 3.3 | 4,596.1 | 2.3 | 6,876.2 | 4.6 |
| 2020 | 6,552.9 | 3.1 | 5,070.7 | 2.0 | 8,302.4 | 3.8 |
| 2025 | 7,533.6 | 2.8 | 5,530.7 | 1.8 | 9,908.5 | 3.6 |
| 2030 | 8,592.7 | 2.7 | 5,981.4 | 1.6 | 11,727.0 | 3.4 |
| 2035 | 9,744.9 | 2.5 | 6,429.8 | 1.5 | 13,794.9 | 3.3 |
| 2040 | 11,006.8 | 2.5 | 6,881.5 | 1.4 | 16,155.8 | 3.2 |
| 2045 | 12,396.5 | 2.4 | 7,342.5 | 1.3 | 18,864.2 | 3.1 |
| 2050 | 13,933.5 | 2.4 | 7,817.2 | 1.3 | 21,978.2 | 3.1 |

[a]Actual reported traffic for 1995.

been labeled Fa through Fe for brevity; these labels, when combined with the appropriate technology assumption designator (1 or 2; see Section 9.4.1.2), form the complete designator for the FESG scenarios used throughout the rest of this report.

Global traffic from the model projections was apportioned over 45 regional traffic flows with a separate market share model because certain regions grow faster than others, and the correct distribution of traffic is important in the calculation of the effects of emissions on the atmosphere. In this procedure, regional traffic flows were expressed as a share of the global market; using the market share and historical growth patterns ensures consistency between regional flows and the global forecast. The underlying assumption of this procedure is that each regional share approaches its ultimate share of the total market asymptotically. Mature markets tend to have declining shares approaching an asymptotic value, whereas developing markets tend to increase their shares. Adjustments of traffic flows were made so that the "top-down" traffic projections of the FESG global model were matched by a reasonable "bottom-up" distribution of regional traffic flows. These traffic flows include all traffic in all regions, and regional variations in growth rates are highlighted. Factors that affect the operations of military and general aviation aircraft were also estimated, and projections were made of the growth of these sectors (CAEP/4-FESG, 1998).

### *9.4.1.2. FESG Technology Projections*

Calculations of fuel burned and $NO_x$ emissions produced by the 2050 scheduled fleet were made by applying projections of overall improvement in fleet fuel efficiency and emission characteristics to regional traffic flows and summing the results. These projections were created from technology-level estimates for new aircraft over time made by a working group of the International Coordinating Council of Aerospace Industries Associations (ICCAIA) (Sutkus, 1997); they are discussed in Section 7.5.5. A "fleet rollover" model was used to project a fleet average fuel efficiency trend, using characteristics of the present-day fleet and traffic demand from the FESG scenarios (Greene and Meisenheimer, 1997). The ICCAIA projections were made for two technology scenarios. The first scenario assumes that fuel efficiency and $NO_x$ reduction will be considered in the design of future aircraft in a manner similar to the current design philosophy. The second technology scenario assumes a more aggressive $NO_x$ reduction design strategy that will result in smaller improvements in fuel efficiency. The assumptions associated with the two technology scenarios are given in Table 9-11. The basis for projections of aircraft emissions made by FESG for the year 2050 was the 3-D NASA emissions scenarios for the year 2015 discussed in Section 9.3.2. The NASA 2015 emissions inventory was factored on the basis of the product of the ratios of regional traffic (as departures), fleet fuel efficiency, and fleet $EI(NO_x)$ as calculated for 2050 over the same values in 2015. For all flights in a given region:

$$NO_x\ \text{Emissions}_{2050} = NO_x\ \text{Emissions}_{2015} \times (\text{regional traffic}_{2050}/\text{regional traffic}_{2015}) \times (\text{fleet fuel efficiency}_{2050}/\text{fleet fuel efficiency}_{2015}) \times (\text{fleet } EI(NO_x)_{2050}/\text{fleet } EI(NO_x)_{2015})$$

Figure 9-18 shows the trend for average new production and fleet average fuel efficiency as a function of time, derived from ICCAIA inputs and the fleet rollover model for the FESG high-demand traffic growth scenario. The average $NO_x$ emission index for the scheduled fleet over the same time period is shown in Figure 9-19. The 2050 fleet average values used in the calculation of emissions from scheduled traffic as well as the baseline 2015 value are given in Table 9-12 (Sutkus, 1997). Fleet fuel efficiency is predicted to improve by about 30% between 2015 and 2050.

***Table 9-11**: ICCAIA $NO_x$ and fuel-efficiency technology assumptions for 2050.*

| Technology Scenario | Fuel Efficiency Increase by 2050 | LTO $NO_x$ Levels |
|---|---|---|
| Design for fuel efficiency and $NO_x$ reduction | Average of production aircraft will be 40–50% better relative to 1997 levels | Fleet average will be 10–30% below CAEP/2 limit by 2050; fleet average $EI(NO_x)$ = 15.5 in 2050 |
| Design for aggressive $NO_x$ reduction | Average of production aircraft will be 30–40% better relative to 1997 levels | Average of production aircraft will be 30–50% below CAEP/2 limit by 2020 and 50–70% below CAEP/2 limit by 2050; fleet average $EI(NO_x)$ = 11.5 in 2050 |

Traffic in the FSU and the People's Republic of China has not historically been reported in airline schedule databases such as the OAG. Fuel burned and emissions from aviation in these regions were estimated individually and projected to 2015 (Mortlock and Van Alystyne, 1998), then extended to 2050 (CAEP/4-FESG, 1998).

### *9.4.1.3. FESG Emissions Scenario Results*

Results of calculations of fuel burned and $NO_x$ emissions for the year 2050 based on the long-term scenarios described above are given in Table 9-13. The FESG complete scenarios are identified below and in the remainder of this chapter by combining the demand scenario (e.g., Fa) with the technology scenario number (e.g., Fa1, Fe2).

## *9.4.2. DTI 2050 Scenarios*

The DTI projection for air traffic and emissions for 2050 (Newton and Falk, 1997) has been developed from the DTI traffic and fleet forecast demand model, in conjunction with data from the ANCAT/EC2 inventory. The forecast model was developed from DTI's global and regional traffic forecast models for passenger and freight traffic. Fuel consumption trends were estimated with a fleet fuel efficiency model, and fleet emissions performance were estimated on the basis of assumed regulatory change. Finally, appropriate fuel and emissions factors were calculated to estimate 2050 figures from the base year; these factors were then applied to the 1992 ANCAT/EC2 emissions inventory to produce gridded results for the 2050 scenario.

The DTI model relates air traffic demand in RPKs with regional and global economic performance as reflected in GDP trends, as was the case with the ANCAT/EC2 2015 forecast. Generally, a load factor of 70% is assumed to estimate ASKs (capacity) from traffic demand. Long-term traffic demand is also assumed to be modified by the same assumptions on fares pricing, market maturity, and so forth that the ANCAT/EC2 2015 forecast used. Capacity estimates are converted to fuel consumption

***Table 9-12**: Projected scheduled fleet fuel efficiency (Sutkus, 1997).*

| | Scheduled Fleet Fuel Efficiency (ASK $kg^{-1}$ Fuel) | |
|---|---|---|
| 2015 NASA Inventory | 41.8 | |
| **Traffic Scenario** | **Technology Scenario 1** | **Technology Scenario 2** |
| Demand scenario Fa | 53.6 | 51.8 |
| Demand scenario Fc | 53.1 | 51.4 |
| Demand scenario Fe | 54.0 | 52.0 |

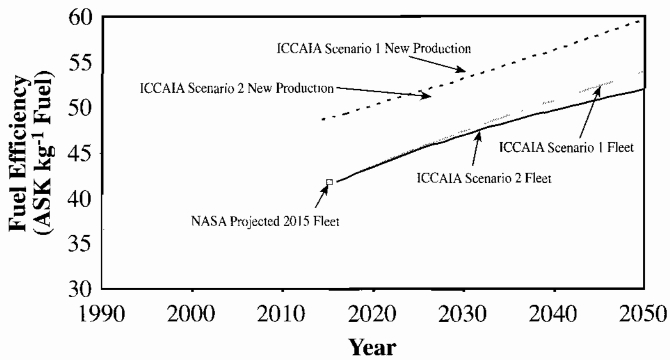


**Figure 9-18**: Fuel efficiency trends to 2050 corresponding to the two ICCAIA technology scenarios for the FESG high traffic demand case.

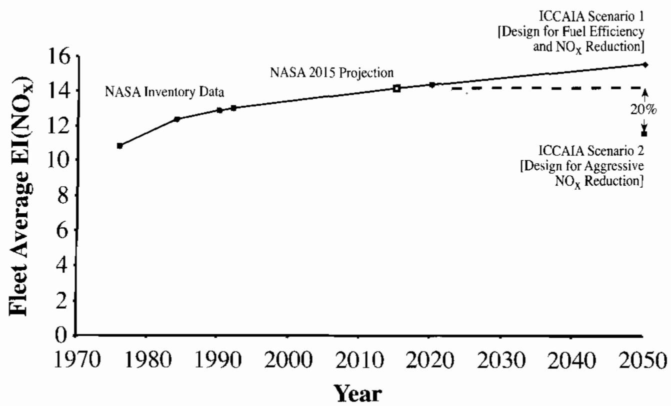


**Figure 9-19**: Fleet average trends in $EI(NO_x)$ showing projections for the two ICCAIA technology scenarios.

***Table 9-13**: Results of FESG year 2050 scenarios calculations.*

| Sector | Fa1 | Fa2 | Fc1 | Fc2 | Fe1 | Fe2 |
|---|---|---|---|---|---|---|
| *Calculated Fuel Burned (Tg)* | | | | | | |
| Scheduled | 396.1 | 410.8 | 224.0 | 232.3 | 620.0 | 643.9 |
| Charter | 21.4 | 22.2 | 12.1 | 12.6 | 33.5 | 34.8 |
| FSU/China | 30.3 | 31.4 | 8.8 | 9.1 | 67.5 | 70.1 |
| General Aviation | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 |
| Civil Subtotal | 456.6 | 473.2 | 253.8 | 262.8 | 729.8 | 757.7 |
| Military | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 |
| Global Total | 471.0 | 487.6 | 268.2 | 277.2 | 744.3 | 772.1 |
| *Calculated $CO_2$ Emissions (Tg C)* | | | | | | |
| Scheduled | 340.7 | 353.3 | 192.7 | 199.7 | 533.2 | 553.7 |
| Charter | 18.4 | 19.1 | 10.4 | 10.8 | 28.8 | 29.9 |
| FSU/China | 26.0 | 27.0 | 7.5 | 7.8 | 58.1 | 60.3 |
| General Aviation | 7.6 | 7.6 | 7.6 | 7.6 | 7.6 | 7.6 |
| Civil Subtotal | 392.7 | 407.0 | 218.2 | 226.0 | 627.7 | 651.6 |
| Military | 12.4 | 12.4 | 12.4 | 12.4 | 12.4 | 12.4 |
| Global Total | 405.1 | 419.4 | 230.6 | 238.4 | 640.1 | 664.0 |
| *Calculated $NO_x$ Emissions (Tg as $NO_2$)* | | | | | | |
| Scheduled | 6.1 | 4.7 | 3.5 | 2.7 | 9.6 | 7.4 |
| Charter | 0.4 | 0.3 | 0.2 | 0.2 | 0.6 | 0.4 |
| FSU/China | 0.5 | 0.3 | 0.1 | 0.1 | 1.0 | 0.8 |
| General Aviation | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Civil Subtotal | 7.0 | 5.4 | 3.9 | 3.0 | 11.3 | 8.7 |
| Military | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Global Total | 7.2 | 5.5 | 4.0 | 3.1 | 11.4 | 8.8 |
| *Calculated Fleet Average EI($NO_x$) [g $NO_x$ (as $NO_2$) $kg^{-1}$ fuel burned]* | | | | | | |
| Scheduled | 15.5 | 11.5 | 15.5 | 11.5 | 15.5 | 11.5 |
| Charter | 16.7 | 12.4 | 16.7 | 12.4 | 16.8 | 12.4 |
| FSU/China | 14.9 | 11.1 | 14.9 | 11.1 | 14.9 | 11.0 |
| General Aviation | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 |
| Civil Subtotal | 15.4 | 11.5 | 15.3 | 11.4 | 15.4 | 11.5 |
| Military | 8.7 | 8.7 | 8.7 | 8.7 | 8.7 | 8.7 |
| Global Total | 15.2 | 11.4 | 15.0 | 11.3 | 15.3 | 11.4 |

estimates by using the concept of traffic efficiency as described in Section 9.3.2 and a fuel efficiency trend for the scenario period. Model coverage includes all global aviation markets, but separate fuel consumption estimates are made for freight and for the FSU on the basis of aligning growth with global civil passenger market trends.

The scenario modeled for 2050 assumes that sufficient aviation infrastructure would be available to accommodate the forecast increase in traffic. No new city pairs are introduced during the scenario period, and aircraft flight profiles remain unaltered from the present day; altitude, speed, and method of operation are assumed to be the same as present-day values, even for larger aircraft types (600+ seats) that are assumed to enter service beginning in about 2005. All traffic is assumed to be carried by a subsonic aircraft fleet (i.e., no HSCT would be operating by 2050). The model forecasts traffic growth to be positive throughout the scenario, but growth rate declines during the period. Decadal capacity growth rates—actual and forecast—are given in Table 9-14. The traffic forecast includes civil and freight operations as well as civil charter and business jet traffic but excludes military aviation activity and possible future supersonic operations.

Fuel usage was determined for the base year fleet from the capacity offered in that year (ASKs) and the fleet's traffic efficiency (ASK per kg fuel). A fuel efficiency trend suggested by Greene (1992) and modified by DTI was included as a scenario parameter, as given in Table 9-15.

The traffic efficiency of the fleet over the scenario period was estimated to range from 30 ASK $kg^{-1}$ in the base year 1992 to 48 ASK $kg^{-1}$ in 2050 (a 60% improvement). This estimate was based on the performance of existing aircraft types and forecasts of the type and number of aircraft (categorized by seat band and technology level) that might be flying in 2050. Future aircraft types included size developments to 799 seats.

A major scenario element was the $NO_x$ reduction technology assumption. Current technology will allow engines to achieve reductions of around 30% below the current certification level (CAEP/2 standards). The basis of the technology scenario was that $NO_x$ regulations would be made considerably more stringent than today and that the manufacturing industry would develop appropriate technology solutions. This development was modeled by assuming that from 1992:

- CAEP/2 certification standard applies to all new production from 2000
- 30% reduction in ICAO recommended limits from CAEP/2 in 2005
- 60% reduction from CAEP/2 phased in equally over 8 years from 2035.

With a fleet development trend determined by the capacity forecast, the rate of introduction of the scenario above implies a global fleet emissions index trend that is as compatible with the relatively modest fuel efficiency assumption given in Table 9-16. The fleet EI($NO_x$) of 7.0 implies widespread use of ultra-low $NO_x$ technology (Section 7.5). The total calculated fuel burned and emissions for 2050 under the DTI/ANCAT scenario are given in Table 9-17.

***Table 9-14**: Actual and forecast global capacity growth rates used in the DTI model.*

| Year | ASK Annual Global Growth Rate (%) |
|---|---|
| 1994 | 5.36 |
| 2000 | 5.16 |
| 2010 | 4.82 |
| 2020 | 3.62 |
| 2030 | 3.01 |
| 2040 | 2.49 |
| 2050 | 1.72 |

***Table 9-15**: Assumed annual improvements in fuel efficiency in DTI model.*

| Year | Annual Improvement in Fuel Efficiency (%) |
|---|---|
| 1991–2000 | 1.3 (Greene, 1992) |
| 2001–2010 | 1.3 (Greene, 1992) |
| 2011–2020 | 1.0 (DTI extrapolation) |
| 2021–2030 | 0.5 (DTI extrapolation) |
| 2031–2040 | 0.5 (DTI extrapolation) |
| 2041 on | 0.5 (DTI extrapolation) |

***Table 9-16**: Trend of civil fleet EI($NO_x$) in DTI projections.*

| Year | EI($NO_x$) |
|---|---|
| 1992 | 11.1 |
| 2010 | 10.73 |
| 2020 | 10.43 |
| 2030 | 10.3 |
| 2040 | 9.5 |
| 2050 | 7.0 |

***Table 9-17**: Results of DTI 2050 projections (military operations not included).*

| Scenario | Traffic ($10^9$ RPK) | Fuel (Tg) | $NO_x$ (Tg $NO_2$) | EI($NO_x$) |
|---|---|---|---|---|
| DTI | 18106 | 633.2 | 4.45 | 7.0 |

### 9.4.3. *Environmental Defense Fund Long-Term Scenarios*

EDF has produced projections of total traffic demand, fuel use, and emissions through 2100 (Vedantham and Oppenheimer, 1994, 1998). The EDF projections use a logistic model to simulate the stages of demand growth in aviation markets, focusing particularly on demand growth in developing countries (where aviation has only recently become a commonplace travel mode). Two sets of aviation demand scenarios—base-level and high-level—describe traffic under each of the six IPCC 1992 scenarios (IS92a through IS92f) for global expectations of gross national product (GNP), population, and emissions (Leggett *et al.*, 1992). Data produced are regional and global totals.

The model logic incorporates the assumption (based on observation) that latent demand in a region previously not served by airlines will result in an initial period of rapid growth; once an airport network is in place, business and personal habits will incorporate the new transport option, causing a period of continuing strong growth rates. Barring unforeseen developments, the experience of some OECD nations suggests that aviation demand will eventually reach maturity, and relative growth rates will slow as the market approaches saturation. Continued growth of GNP and population imply continuing, albeit slow, growth in demand, even over the very long term.

EDF uses a logistic model with a time-varying capacity to model the dynamics in several sectors of rapid expansion, continued growth, and eventual slowdown in growth rates without imposing a zero growth-rate ceiling. Growth rates and market capacities for different regions of the world were chosen after a review of economic and aviation market history in industrial nations. The demand model is consistent with the history of the U.S. domestic market.

The EDF model sorts the nations of the world into five economic groups (see Table 9-18). For each of the five economic groups, the three sectors of civil business passenger, civil personal passenger, and civil freight are modeled as logistics with

***Table 9-18**: Definition of regional economic groups in the EDF model.*

| Group | Members |
|---|---|
| 1 | OECD members, except Japan |
| 2 | Asian newly industrialized countries (NICs), Japan |
| 3 | China and the rest of Asia |
| 4 | Africa, Latin America, Middle East |
| 5 | Former Soviet Union (FSU), Eastern Europe |

time-varying market capacities. The civil business passenger and civil freight sectors experience logistic expansion toward a time-varying capacity level that is proportional to the nation's GNP.

The model assumes that expansion in business travel is accompanied by expansion in personal travel, which includes tourism and leisure visits. Personal travel by air has high income elasticity, and aviation demand will increase rapidly when a poor nation experiences an economic boom and per capita income increases. Depending on the income distribution, there can be significant demand for aviation even in countries with very low per capita incomes (Atkinson, 1975). As incomes rise and seat prices (as well as cargo costs) fall, growth in aviation demand will result from the penetration of aviation services into lower income brackets (Boeing, 1993). The civil personal passenger sector experiences logistic expansion toward a time-varying capacity level proportional to the nation's population (the model does not account for possible feedback relationships between GNP and population). The military and general aviation sectors do not experience logistic expansion; both sectors grow nominally, at the same rate as global GNP. The mathematical basis of the model and further details on the assumptions are given by Vedantham and Oppenheimer (1994, 1998).

The base-demand and high-demand sets include expected start date for market expansion, market capacity levels, and maturity period length. These assumptions for the two demand sets reflect implicit assumptions about diverse social factors, including travel trends in developing countries (Gould, 1996), penetration of future telecommunications technologies, and development of competing modes of transportation. Assumptions on start dates of aviation market expansion for rapidly developing economies, slowly developing economies, and post-Communist economies reflect EDF's own assessment of near-term economic expectations and were not made in relation to IPCC scenarios. Prior to the start date, demand is assumed to grow nominally, at the same rate as global GNP. The base-demand and high-demand sets include assumptions on market capacity levels based on multiples of 2 (base-demand) and 3 (high-demand) relative to the 1990 demand levels for Economic Group 1 (OECD less Japan), because these markets are closest to maturity today.

EDF's analysis of the history of the U.S. domestic market concluded that there was approximately a 70-year period from start of market expansion to maturity. The model assumes that nations that are building their airport infrastructure today may well attain market maturity faster because they will benefit from technological improvements and some fraction of their populace will be more familiar with lifestyle and business habits that incorporate aviation. Another region-specific assumption was that markets in the post-Communist economies may mature faster because they have undergone industrialization.

The six IPCC scenarios for GNP and population, combined with the two demand sets described above, provide a total of 10 demand projections (because the IS92a and IS92b scenarios share the same GNP and population expectations). Figure 9-20 shows five of the global demand scenarios; sharp upswings when different regions start expansion are clearly visible. Annotations attached to the curves are shorthand nomenclatures for the scenarios used in this report.

Under the IS92a scenario (the IPCC base case), the base-demand level in 2050 is higher than the 1990 level by a factor of 10.7 and has an average annual demand growth rate of 4.03% over the 60-year forecast period (forecasts to 2100 are given by Vedantham and Oppenheimer, 1998). For the base-demand set, the range of traffic demand expected for different population and GNP estimates spans a factor of almost 5 in 2050; the full range across all 10 scenarios spans a factor of more than 20. Assumptions about rates of expansion and maturity have a sizable impact: The high-demand projection for the IS92a scenario in 2050 is 78% higher than the base-demand value.

The 10 demand scenarios produced by the EDF model are synthesized with expectations for fuel efficiency improvement and changes in emissions indices to produce fuel use, $CO_2$ emissions, and $NO_x$ emissions scenarios.

Although fuel efficiency has increased steadily over the past few decades, improvements in fuel efficiency are becoming less dramatic over time. The technology projections of the EDF model use a constant-capacity logistic that extrapolates Greene's (1992) forecast for a base-case annual increase

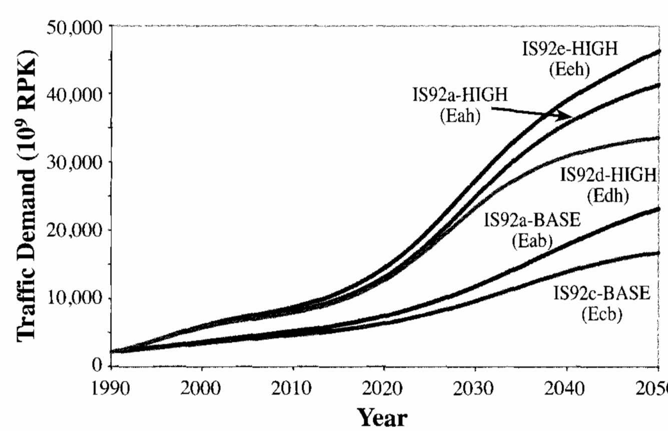


**Figure 9-20**: EDF global aviation demand projections.

***Table 9-19**: Excerpt of EDF results—demand, fuel use, $CO_2$, % of global $CO_2$, and $NO_x$.*

| **IPCC Scenario** | **Factor** | 1990 | 2000 | **Year** 2015 | 2025 | 2050 |
|---|---|---|---|---|---|---|
| IS92a Base (Eab) | Demand ($10^9$ RPK) | 2,171 | 3,629 | 6,115 | 9,339 | 23,256 |
| | Fuel Use (Tg) | 179 | 258 | 374 | 544 | 1,143 |
| | $CO_2$ (Tg C) | 154 | 222 | 322 | 468 | 983 |
| | Percentage of Global $CO_2$ | 2.1% | 2.6% | | 3.8% | 6.8% |
| | $NO_x$ (Tg) | 1.96 | 2.57 | 3.28 | 4.42 | 7.88 |
| IS92a High (Eah) | Demand ($10^9$ RPK) | 2,171 | 5,801 | 9,954 | 18,332 | 41,392 |
| | Fuel Use (Tg) | 179 | 395 | 610 | 1,123 | 2,086 |
| | $CO_2$ (Tg C) | 154 | 340 | 525 | 966 | 1794 |
| | Percentage of Global $CO_2$ | 2.1% | 4.1% | | 7.9% | 12.4% |
| | $NO_x$ (Tg) | 1.96 | 3.92 | 5.34 | 9.12 | 14.39 |
| IS92c Base (Ecb) | Demand ($10^9$ RPK) | 2,171 | 3,447 | 5,337 | 7,802 | 16,762 |
| | Fuel Use (Tg) | 179 | 243 | 325 | 455 | 837 |
| | $CO_2$ (Tg C) | 154 | 209 | 280 | 391 | 720 |
| | Percentage of Global $CO_2$ | 2.1% | 2.8% | | 4.5% | 9.6% |
| | $NO_x$ (Tg) | 1.96 | 2.42 | 2.85 | 3.70 | 5.77 |
| IS92d High (Edh) | Demand ($10^9$ RPK) | 2,171 | 5,729 | 9,647 | 17,619 | 33,655 |
| | Fuel Use (Tg) | 179 | 390 | 592 | 1,082 | 1,689 |
| | $CO_2$ (Tg C) | 154 | 336 | 510 | 932 | 1,453 |
| | Percentage of Global $CO_2$ | 2.1% | 4.5% | | 10.0% | 16.2% |
| | $NO_x$ (Tg) | 1.96 | 3.88 | 5.19 | 8.79 | 11.64 |
| IS92e High (Eeh) | Demand ($10^9$ RPK) | 2,171 | 5,964 | 10,850 | 20,202 | 46,362 |
| | Fuel Use (Tg) | 179 | 408 | 668 | 1,234 | 2,297 |
| | $CO_2$ (Tg C) | 154 | 351 | 574 | 1,061 | 1,975 |
| | Percentage of Global $CO_2$ | 2.1% | 3.9% | | 7.0% | 9.8% |
| | $NO_x$ (Tg) | 1.96 | 4.05 | 5.85 | 10.02 | 15.84 |

of 1.3% in fleet-wide fuel efficiency from 1989 to 2010. Significant differences in fuel efficiency exist today across regions, and there may be a tendency toward higher fuel efficiency in wealthier regions. The EDF model assumes differences in fuel efficiency across economic groups and builds projections on the assumption that the technology gap between wealthier and poorer nations will close over time.

The $NO_x$ emissions scenarios reflect changes in EI($NO_x$) based on a constant-capacity logistic that extrapolates a best-fit approximation to the 1993 NASA numbers for EI($NO_x$) in 1990 and 2015 (Stolarski and Wesoky, 1993). The model does not reflect specific technology choices for fuel efficiency or changes in EI($NO_x$), although the fleet EI($NO_x$) of 6.9 that results from the extrapolation is in the ultra-low technology regime. Results for all scenarios are summarized in Table 9-19.

Figure 9-21 shows $CO_2$ emissions scenarios [which assume a constant EI($CO_2$) of 3.16]. Under the base IS92a scenario, $CO_2$ emissions grow at an annual rate of 3.2% to reach 983 Tg C in 2050—an increase of a factor of 6.6. For all scenarios, projected $CO_2$ emissions climb rapidly after 2015. For the IS92c scenario (which reflects low population and GNP growth) under both demand sets, the level of $CO_2$ emissions in 2100 is lower than that in 2050, reflecting a successful catch-up effect whereby technological improvements have compensated for demand growth (Vedantham and Oppenheimer, 1998).

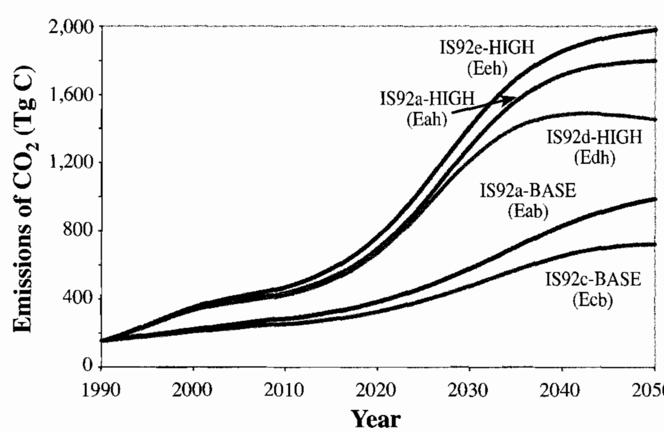


**Figure 9-21**: EDF $CO_2$ emissions projections.

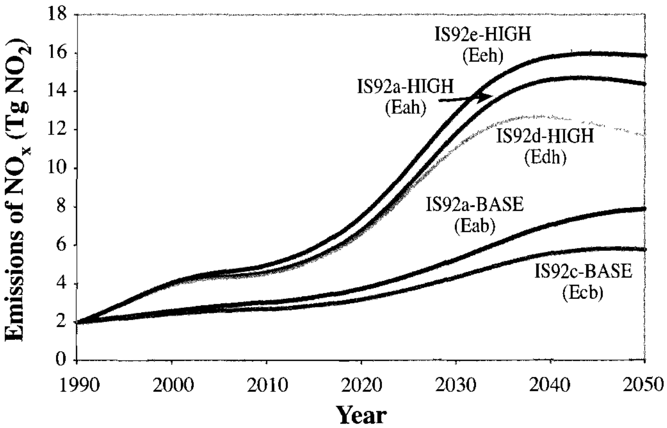


**Figure 9-22**: EDF $NO_x$ emissions projections.

Comparing the EDF scenarios for aviation's $CO_2$ emissions projections with the IPCC scenarios for total anthropogenic $CO_2$ emissions (including emissions from energy consumption and deforestation) provides a benchmark measure of the environmental importance of the aviation sector. For the base-demand IS92a scenario, aviation's share of global $CO_2$ emissions rises from its current value of 2.1% to a level of 3.8% in 2025 and 6.8% in 2050. Across all scenarios, aviation's share of global $CO_2$ emissions ranges between 3.3 and 10% in 2025 and between 5.6 and 17.6% in 2050. These scenarios imply that aviation may become a significant contributor to global $CO_2$ emissions.

Figure 9-22 shows the $NO_x$ emissions scenarios; these scenarios incorporate the effects of fuel efficiency improvements as well as changes in EI($NO_x$). For the base-demand IS92a scenario, $NO_x$ emissions rise sharply from almost 2 Tg (as $NO_2$) in 1990 to 7.9 Tg in 2050. Because total $NO_x$ emissions are reduced as a result of fuel efficiency improvements and EI($NO_x$) reduction, technological improvement can compensate for a greater fraction of demand growth than in the case of $CO_2$ emissions.

Table 9-19 presents an excerpt of EDF model results of traffic demand, fuel burned, and emissions of $CO_2$ and $NO_x$ through the year 2050 for the several sets of assumptions. The three-letter designators for the EDF scenarios (e.g., Eab, Eeh) are used throughout this report.

### 9.4.4. *World Wide Fund for Nature Long-Term Scenario*

A study by WWF addresses future aviation demand by analyzing load factors and capacity constraints, particularly in the freight market (Barrett, 1994). Analysis of historical data shows that increases in the number of seats per aircraft have begun to level off. The study examines the effects of pollution control strategies such as phasing out of air freight and policies to encourage intermodal shifts to road and rail. Technological options for reducing the environmental impact of aviation (such as operational improvements, changes in cruise altitude and alternative fuel sources) are examined. In particular, these models consider the feasibility that increases in load factors (percentage of total passenger seats that are occupied) could increase fuel efficiency per seat-km for aviation. The model evaluates a wide range of policy and operational choices, including a 100% load factor and a 100% fuel tax.

The model includes explicit assumptions of fixed growth rates in leisure travel, business travel, average trip length for passenger and freight traffic, and freight tonnage. It assumes that passenger load factors rise to 75% by 2020 in the base case. Constant rates of improvement are assumed for aircraft size, airframe efficiency, and EI($NO_x$).

With an annual growth rate of 5.2%, demand rises by a factor of more than 12 between 1991 and 2041 in the "business-as-usual" case. Proposed policies, including changes in load factor, and technological improvements result in a forecast for demand increase of about a factor of 3 in the "demand management" case. Carbon emissions in 2041 constitute 550 Tg C, and aviation's share of global carbon emissions rises to 15% by 2041.

### 9.4.5. *Massachusetts Institute of Technology Long-Term Scenarios*

A study of the long-term future mobility of the world population has been undertaken at MIT. This study constructed scenarios based on the simple yet powerful assumption that time spent and share of expenditures on travel remain constant (Zahavi, 1981), on average, over time and across regions of the globe (Schafer and Victor, 1997). Stability of average time budgets for travel (motorized and nonmotorized) is substantiated by a considerable amount of aggregate historical data. Although there is some variability in travel budgets from poorer to richer nations, within each society travel budgets have generally followed a predictable pattern—rising with income and motorization and stabilizing at 10–15%.

Using the constant travel budget hypothesis, Schafer and Victor (1997) produced global passenger mobility scenarios for 11 world regions and four transport modes for the period 1990–2050. Adding estimates of changes in the energy intensity of transportation modes, they also generated scenarios of $CO_2$ emissions from passenger transport (see Table 9-20).

The high-speed travel category includes aviation, but the aviation portion of high-speed travel is not explicitly characterized. Results of this model projection therefore cannot be used directly in evaluations of the effect of aviation on the atmosphere, nor can they be directly compared to other long-term projections of emissions from aviation.

## 9.5. High-Speed Civil Transport (HSCT) Scenarios

The technology for commercial (supersonic) HSCT is being developed in the United States, Europe, and Japan. The goal is to develop an aircraft that can carry approximately 300 passengers, with a 9,260-km range, cruising at Mach 2.0–2.4 at altitudes of 18–20 km. As described in Chapter 7, NASA has an aggressive technology program to develop combustors with $NO_x$ emission levels of 5 g $NO_x$ (as $NO_2$) per kg fuel burned at supersonic cruise conditions. The HSCT is expected to fly supersonically only over water because of the need to mitigate sonic booms over populated land masses. The potential market for the HSCT is limited by economic and environmental considerations.

### *9.5.1. Description of Methods*

3-D emissions inventories of fuel burned, $NO_x$, CO, and unburned HC for fleets of 500 and 1,000 active (high utilization) HSCTs have been developed based on market penetration models and forecasts of air traffic in 2015 (Baughcum *et al.*, 1994; Baughcum and Henderson, 1995, 1998). Although such large fleets clearly will not be in operation by 2015, the year was chosen as a base year because detailed industry projections of air traffic on a route-by-route basis are available only to that time period. Although the introduction of an economical HSCT may stimulate total traffic growth by an unknown amount, the HSCT will certainly displace some traffic from the subsonic fleet on major long-range intercontinental routes. For this study, possible stimulative effects were ignored to reduce the number of variables, and HSCT-generated RPKs were explicitly substituted for subsonic RPKs on a route-by-route basis.

The most recent set of scenarios based on the NASA technology concept aircraft (TCA) HSCT were used for most of the atmospheric impact calculations presented in Chapter 4. It is not clear when HSCT technology will be mature enough for viable commercial service, so fleet sizes and technology levels are treated parametrically.

The projected flight tracks for a fleet of 500 HSCTs above 13-km altitude are shown in Figure 9-23. Because of its speed advantage over subsonic aircraft, the HSCT would likely be used primarily on long intercontinental routes, where that advantage can best be utilized. Because of the sonic boom that trails below the aircraft, the best HSCT routes have a large portion of the flight path over water. These conditions combine to put a majority of HSCT routes at northern mid-latitudes over the North Atlantic and North Pacific.

To project the HSCT fleets and their displacement of subsonic aircraft in the scenarios to 2050, the following procedure was used:

1) 3-D displacement scenarios of subsonic traffic by a fleet of 1,000 active HSCTs was calculated for the year 2015 using differences in the 3-D scenarios calculated for the NASA all-subsonic fleet (Baughcum *et al.*, 1998) and the NASA subsonic fleet in the presence of an HSCT fleet (Baughcum and Henderson, 1998).
2) This subsonic displacement scenario was then scaled for the technology growth factors described in the discussion of the FESG scenario and combined with the HSCT only-scenario (assuming the TCA technology level) and 2050 all-subsonic scenarios.

The 1,000-unit fleet should not be considered a forecast of the actual number of HSCTs that might be in the fleet in 2050. For this sensitivity study, the 1,000-unit value was chosen to represent a fleet that would be the result of a successful HSCT program; this fleet size also was chosen so that previous fleet projections could be used (Baughcum and Henderson, 1998). No changes in fuel efficiency or $NO_x$ emissions technology relative to the assumptions used in the reference were assumed

***Table 9-20**: Results of MIT reference scenario–passenger travel and carbon emissions.*

| | **1990 ($10^{12}$ pkm[a])** | **2050 ($10^{12}$ pkm)** | **1990 ($10^{12}$ mt C)** | **2050 ($10^{12}$ mt C)** |
|---|---|---|---|---|
| *Industrialized* | | | | |
| High-Speed | 1.5 | 32.7 | 0.09 | 0.66 |
| Total | 12.4 | 44.4 | 0.52 | 1.12 |
| *Reforming* | | | | |
| High-Speed | 0.3 | 2.1 | 0.02 | 0.04 |
| Total | 2.3 | 7.1 | 0.07 | 0.20 |
| *Developing* | | | | |
| High-Speed | 0.4 | 7.2 | 0.02 | 0.14 |
| Total | 8.6 | 53.8 | 0.18 | 1.29 |
| *World* | | | | |
| High-Speed | 2.2 | 42.0 | 0.13 | 0.84 |
| Total | 23.3 | 105.3 | 0.77 | 2.61 |

Source: Schafer and Victor (1997); additional data supplied by David Victor (June 1998).
[a]pkm=passenger kilometers.

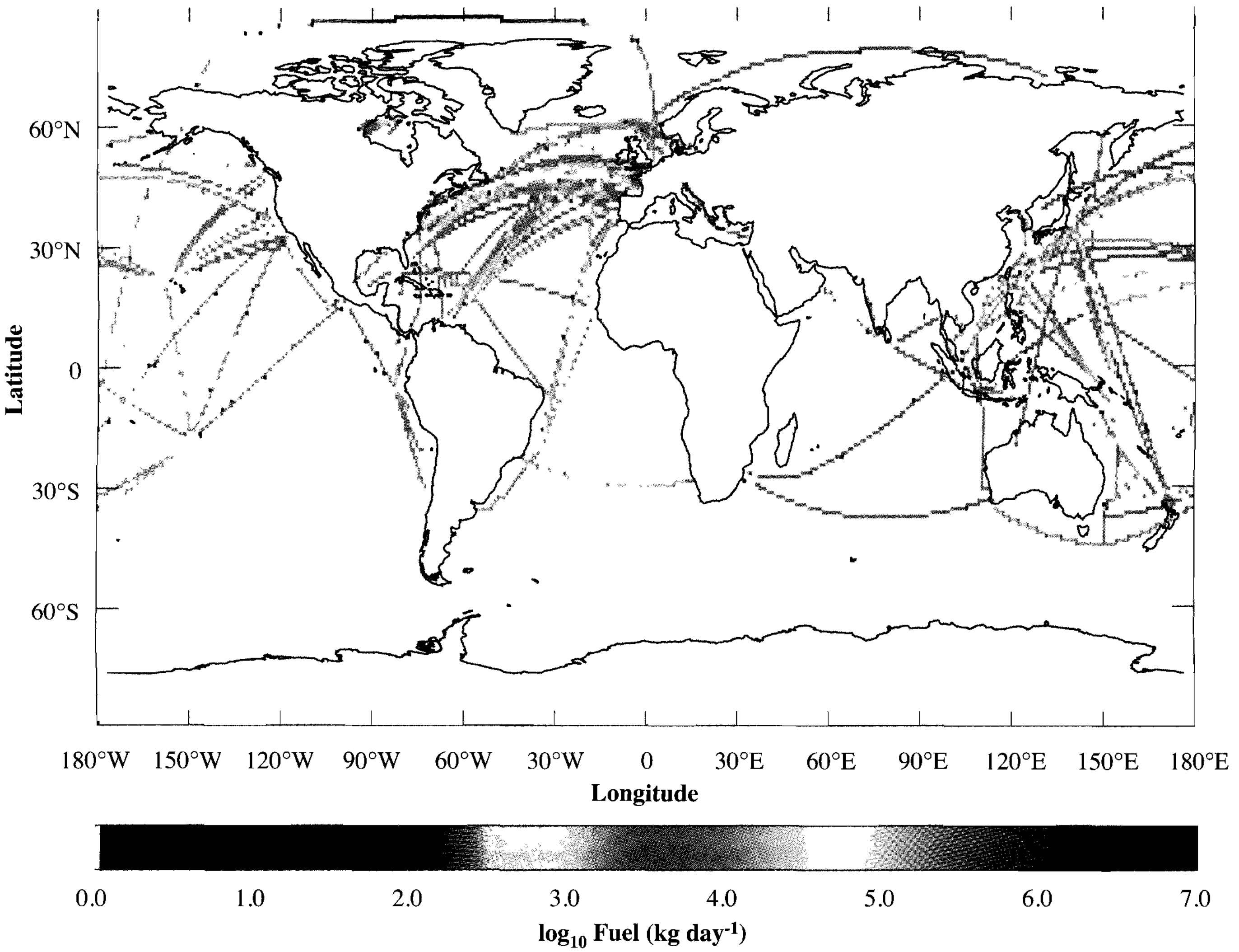


**Figure 9-23**: Flight tracks above 13-km altitude for a fleet of 500 high-speed civil transports (Baughcum and Henderson, 1998).

for the 2050 HSCT. A detailed description of the route system flown by the 1,000 HSCTs is given by Baughcum and Henderson (1998).

### *9.5.2. Description of Results*

Fleet fuel burned with the HSCT was calculated by assuming that the fuel efficiency and $NO_x$ emissions of the subsonic fleet were described by $NO_x$ technology scenario 1, the "fuel efficiency" scenario. Table 9-21 gives the total fleet fuel burned and $NO_x$ emissions with and without the assumed 1,000-unit HSCT fleet. Fleet fuel burned increases as a result of the substitution of less fuel efficient HSCTs for subsonic airplanes (present HSCT designs have about half the fuel efficiency, measured as RPK per fuel burned, of present subsonic airplanes). However, fleet $NO_x$ emissions decrease in spite of the increase in fuel burned because the HSCT is assumed to be designed for very low $NO_x$ emissions [cruise EI($NO_x$) of 5].

A comparison of the altitudinal distributions of fuel use and $NO_x$ emissions between the all-subsonic fleet and a fleet containing subsonic and HSCT aircraft is shown in Figures 9-24 and 9-25 for the FESG year 2050 IS92a scenario. The introduction of an HSCT fleet with EI($NO_x$)=5 combustors would be expected to increase emissions above 12-km altitude and lead to a decrease of $NO_x$ emissions below 12, particularly in the 10-12 km band, assuming that the introduction of an HSCT will cause a displacement of subsonic traffic.

## 9.6. Evaluation and Assessment of Long-Term Subsonic Scenarios

### *9.6.1. Difficulties in Constructing Long-Term Scenarios*

Long-term (beyond 20 years) projections of aviation traffic demand, fleet fuel burned, and fleet emissions are inevitably speculative. Difficulty in forecasting technological developments that might be appropriate for the long term, possible shifts in traffic demand, and myriad uncertainties resulting from human society's development over the period in question all conspire to make long-term projections unreliable—sometimes astoundingly so. Given the state of the aviation industry 50

***Table 9-21**: Results of substitution of 1,000-unit parametric HSCT fleet in 2050.*

| Scenario | Fuel (Tg) | $CO_2$ (Tg as C) | % Change (Fuel) | $NO_x$ (Tg as $NO_2$) | % Change ($NO_x$) | Fleet EI($NO_x$) |
|---|---|---|---|---|---|---|
| Fa1—All Subsonic | 471 | 405 | Base | 7.2 | Base | 15.2 |
| Fa1H—With 1,000 active HSCTs | 557 | 479 | +18 | 7.0 | -2 | 12.6 |
| Fe1—All Subsonic | 744 | 641 | Base | 11.4 | Base | 15.3 |
| Fe1H—With 1,000 active HSCTs | 831 | 715 | +12 | 11.3 | -1 | 13.6 |

years ago (in 1947), it is doubtful that either the technology or the scope of the industry in 1997 could have been forecast. However, because the transport aviation market and aviation technology seem to be maturing, a plausible way of making projections far into the future is to make reasonable extrapolations based on our knowledge of present trends in the world and in the aviation industry. These extrapolations are termed scenarios, rather than forecasts, as outlined in Section 9.1.

### 9.6.2. *Structure and Assumptions*

Before we review the outcomes of the scenario studies in the following section, we consider some differences and similarities between the models. This comparison is restricted to the EDF, DTI, and FESG models. Although the MIT model provides an interesting insight into future travel options based on the thesis of invariant travel time and travel expenditure budgets, it is excluded from this comparison because it provides only a highly aggregated scenario for the future mobility of total motorized passenger traffic; air traffic is only one—albeit important—portion of this picture, and the aircraft component cannot be identified. The WWF aviation scenario for 2041 provides aggregated fuel burned and $CO_2$ emissions projections but does not provide regionally distributed $NO_x$ emissions estimates.

Of the long-term scenarios considered, the EDF, FESG, and DTI studies allow assessment of the impacts of $CO_2$ from aviation. However, only the results from the DTI and the FESG models are suitable for use in chemical transport models for modeling other emissions (see Chapters 2 and 4) and their effects on radiative forcing (see Chapter 6) because they provide gridded data that include a consideration of the potential changes in the spatial distribution of emissions. Only the EDF study provides scenarios for demand from the aviation sector and subsequent global $CO_2$ and $NO_x$ emissions to 2100.

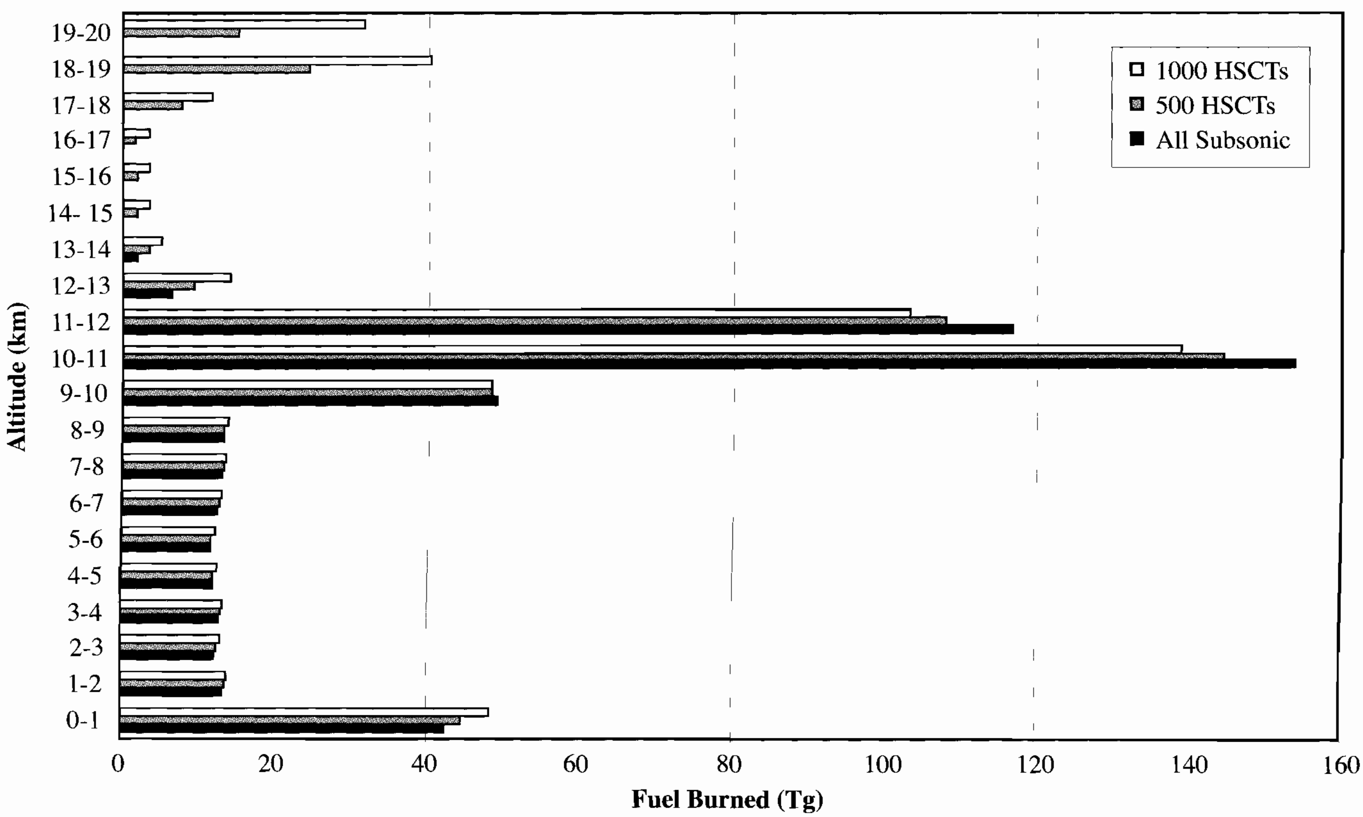


**Figure 9-24**: Altitude distribution of fuel burned—with and without HSCT fleet—based on IS92a scenario (Fa1,2).

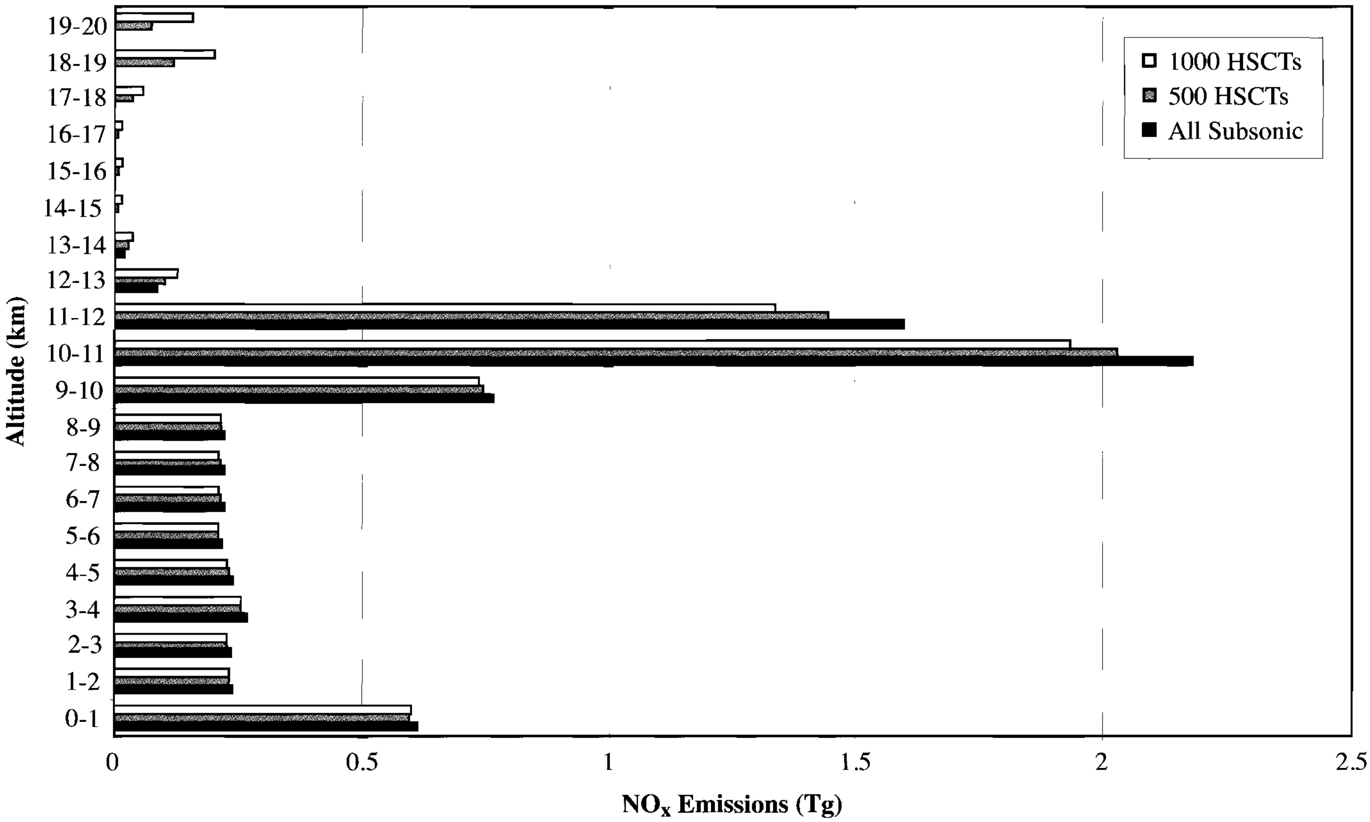


**Figure 9-25**: Altitude distribution of $NO_x$ emissions—with and without HSCT fleet—based on IS92a scenario (Fa1, FaH).

The EDF study provided 10 scenarios based on five different IPCC IS92 world scenarios for the long-term development of world economy and population and two air traffic demand scenarios (base case and high case). The FESG study calculated three air traffic demand scenarios based on the IPCC IS92a, IS92c, and IS92e world scenarios, which were combined with two engine technology scenarios to produce six different emissions inventories.

The FESG scenarios of regional and global air traffic were based on a logistic regression model of traffic demand since 1960 using global GDP as a predictor. The FESG model used a combination of top-down and bottom-up approaches, in which global volumes of civil aircraft flight kilometers were predicted using the regression model for different GDP scenarios. All available information on regions, including regional variation in growth, was then used to disaggregate these global values in a consistent way over 45 traffic flows within and between the regions of the world by using a market share allocation model. Year 2050 values of fuel burned and $NO_x$ emissions for military traffic were estimated separately.

The EDF scenarios also were based on the use of logistic growth curves to model air traffic growth for business and personal travel (plus military and freight traffic). Model parameters were chosen through observation of historical traffic trends in the United States. Regional population was used as a predictor of personal passenger travel, and regional GNP was used as a predictor of business passenger travel and freight demand. Both the FESG and EDF models incorporate the underlying assumption that the chosen parameters are satisfactory predictors of aviation demand and that aviation markets eventually mature.

There are large differences between the EDF and FESG models with respect to the development of emissions scenarios. The EDF model uses a constant capacity logistic to describe fuel efficiency improvements, which extrapolates Greene's (1992) forecast to 2010 with varied rates for five geographic world regions and the military/freight aviation sector. For the trend in fleet EI($NO_x$) a single global logistic model extrapolates from the 1990 and 2015 values. The FESG scenarios are based on two engine technology scenarios developed by ICCAIA for ICAO/FESG and IPCC (see Chapter 7). These scenarios represent an industry perspective on likely future developments in fuel efficiency and $NO_x$ reduction technologies, as well as further potentials and limitations. The fuel efficiency technology element of the DTI scenario was similar in this respect, but a $NO_x$ technology scenario appropriate to stricter emissions regulations was assumed, in which subsonic engine research programs would deliver emissions levels similar to those targeted in the NASA HSCT program.

Additional assumptions are also important to the results of the scenario models. In the EDF model, assumptions about the dates of market expansion and maturity and the ultimate capacity levels chosen for the economic regions strongly influence the outcomes.

The EDF, FESG, and DTI models all use statistics of traffic/air traffic from international organizations and OECD countries, as well as numerous other recently published sources, and adopt one or more of the IPCC IS92 scenarios to describe the long-term development of worldwide economic growth and population. The FESG, EDF, and DTI models also use information from the NASA and ANCAT/EC gridded inventories of traffic flows and related emissions. The FESG models used new, partly proprietary, information from industry as a base to project emissions in the year 2050.

None of the 3-D gridded inventories for 2050 assume any changes in design that would alter the cruise altitudes of subsonic aircraft. Furthermore, no consideration was given in any of the 2050 scenarios reported here to the possible stimulative (or otherwise) effect of HSCT introductions on traffic.

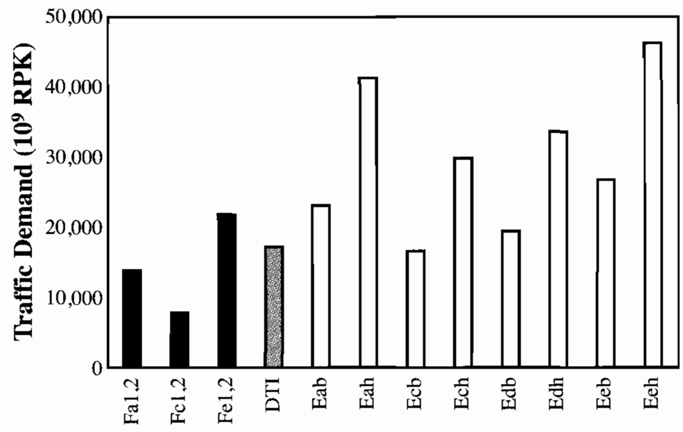


**Figure 9-26**: Comparison of traffic demand in 2050.

### 9.6.3. *Traffic Demand*

Total traffic demand projected for the year 2050 for three of the long-range scenarios is shown in Figure 9-26. The values shown for the FESG model projection do not include military or general aviation traffic. Military and general aviation fuel burned and emissions were estimated separately for the year 2050; they were 3.1 and 1.8% of total fuel burned, respectively (Fa1,2). The demand values shown for the EDF model include military as well as freight demand, with projected billion tonne-km values converted to RPK. The DTI model includes passenger, freight, and business jet traffic but excludes military operations. The WWF model includes passenger and freight only, but a demand value for 2041 was not published.

Although the FESG and EDF models use the same IS92 economic scenarios (IS92 population scenarios also are inputs to the EDF model), the traffic demand projections for 2050 from the EDF model are higher than those of the FESG model by a factor of 1.2 to almost 4, depending on the scenario. The DTI model, which does not directly depend on the IS92 scenarios, projects a traffic demand about 80% that of the FESG high case (Fe1,2).

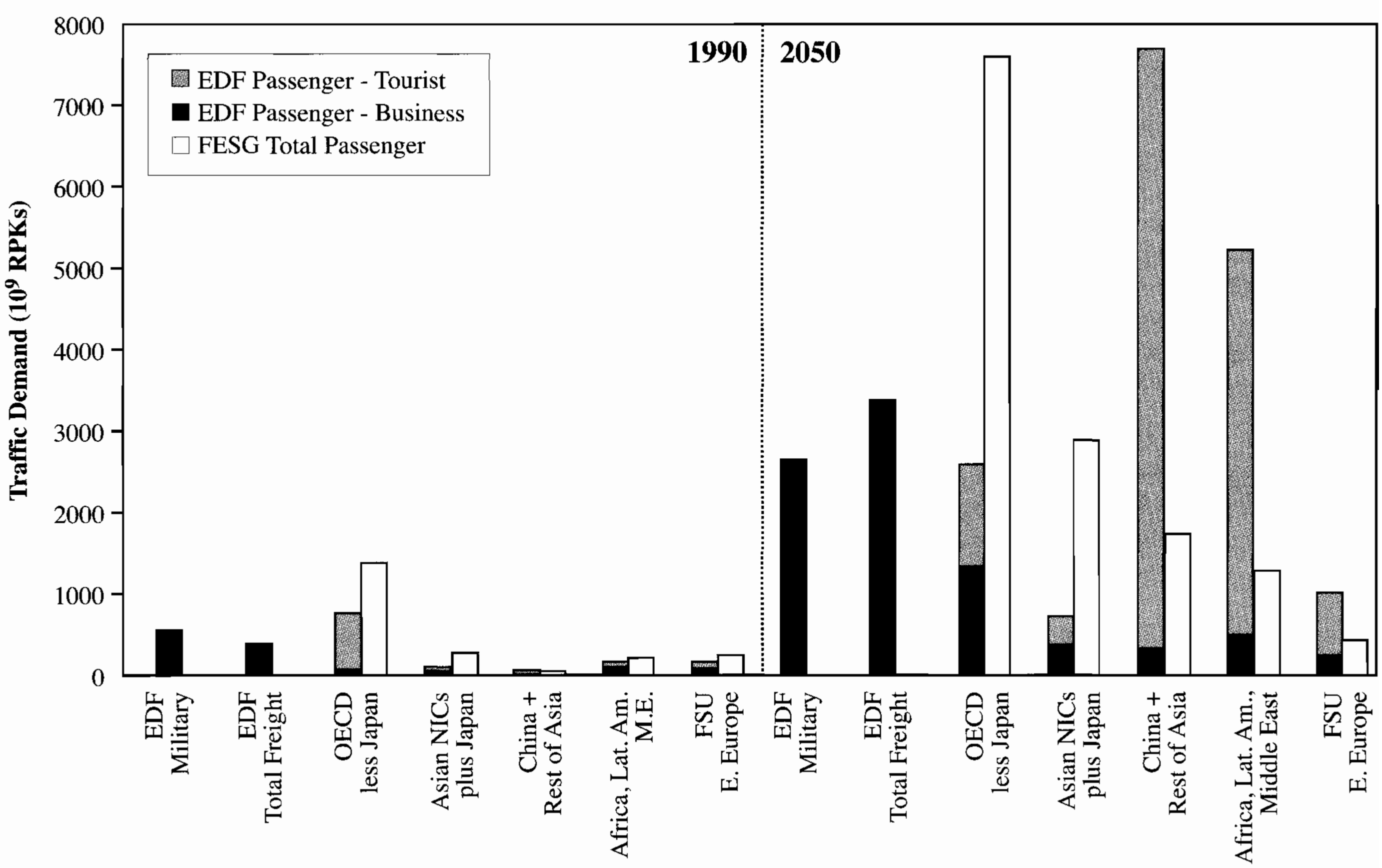


**Figure 9-27**: Comparison of 1990 and 2050 regional demand values based on EDF and FESG models (IS92a scenario).

***Table 9-22***: *Comparison of FESG and EDF model results for year 2050 based on IS92a.*

| Region | 1990 % World GNP | 1990 % World Population | 1990 FESG % Demand | 1990 EDF % Demand | 2050 % World GNP | 2050 % World Population | 2050 FESG % Demand | 2050 EDF % Demand |
|---|---|---|---|---|---|---|---|---|
| 1) OECD, less Japan | 57 | 12 | 63 | 62 | 45 | 8 | 55 | 15 |
| 2) Asian NICs + Japan | 16 | 3 | 13 | 5 | 13 | 2 | 21 | 4 |
| 3) China, Rest of Asia | 6 | 52 | 2 | 5 | 15 | 49 | 12 | 45 |
| 4) Africa, Latin America, Middle East | 9 | 25 | 10 | 14 | 18 | 37 | 9 | 30 |
| 5) FSU, Eastern Europe | 12 | 7 | 11 | 14 | 9 | 5 | 3 | 6 |

Clues to the reasons behind the large differences in projected traffic demand between the FESG and EDF models can be found by examining the details of the results of each model. The EDF model projects passenger business and personal traffic in five world regions, plus military and freight traffic. To make comparisons between the two models, the 45 traffic demand flows (allocated from the global growth projection) in the FESG model were assigned to the five regions used in the EDF model. Demand flows between two of the EDF-defined regions were allocated by assigning 50% of the FESG traffic demand to each region.

On the previous page, Figure 9-27 shows a comparison of traffic demand in 1990 and 2050 from the FESG and EDF models, with demand sorted by region and/or type. The EDF base case demand (Eab) is compared with the Fa1,2 demand scenario. Large differences in the distribution of demand between the two models are apparent: The FESG model assigns the largest share of passenger traffic in 2050 to the OECD area, whereas the EDF model assigns the largest share to the China-Africa area (with personal travel making up the bulk of the demand).

Table 9-22 provides data on passenger demand from the EDF and FESG models by region in 1990 and 2050 and regional distribution of world GNP and population over the same time periods. The basis of both models in this comparison is the IS92a GNP and population scenario. In 1990, the demand distributions of both models are roughly the same and reflect to a great extent the regional distribution of GNP. In 2050, the regional demand distribution from the FESG model reflects the shift in GNP distribution, demonstrating the economics-driven basis of the FESG model. The 2050 FESG values also show that the market share tool has probably underestimated the share of demand in region 4; percentage of GNP has increased from 1990 to 2050, but percentage of demand has decreased.

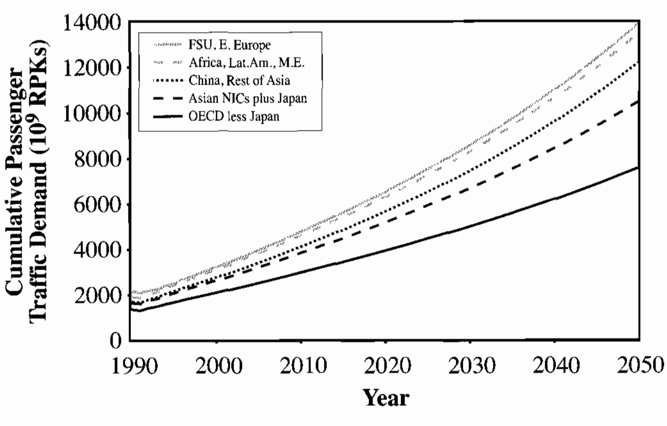


**Figure 9-28**: Cumulative traffic demand (IS92a scenario, Fa1,2).

In contrast, the 2050 demand distribution from the EDF model differs greatly from the distribution of GNP in 2050 and reflects the population-driven basis of much of the EDF model.

The differences between the FESG and EDF models are further illustrated in Figures 9-28 and 9-29, which show the cumulative distribution of traffic growth over time for the IS92a scenario. Figure 9-28 shows the growth and regional proportions of traffic demand as projected by the FESG model. The shares of demand reflect the GDP of each region. Figure 9-29 shows the cumulative distribution of demand for the five regions as projected by the EDF model. The EDF model, unlike the FESG model, projects business and personal passenger demand separately (business demand is a function of GNP; personal demand is a function of population); both sectors of demand are shown in the figure. Notable is the lack of projected growth in personal demand in region 1 (OECD less Japan). Driven by projected slow growth and eventual decline in OECD population, demand growth in this sector is projected to be less than 1% per year after 2005 and negative after 2035. Notable also is the relative lack of growth projected for region 2 (Asian newly industrialized countries + Japan). The effect of the population-driven personal demand sector is shown by the rapid growth in regions 3 (China + rest of Asia) and 4 (Africa, Latin America, Middle East). Personal demand in these two regions is projected by the EDF model to grow at rates exceeding 12% per year for 25 years (region 3) and 10% per year for 20 years (region 4) to create 75% of total passenger demand in 2050 (up from 19% in

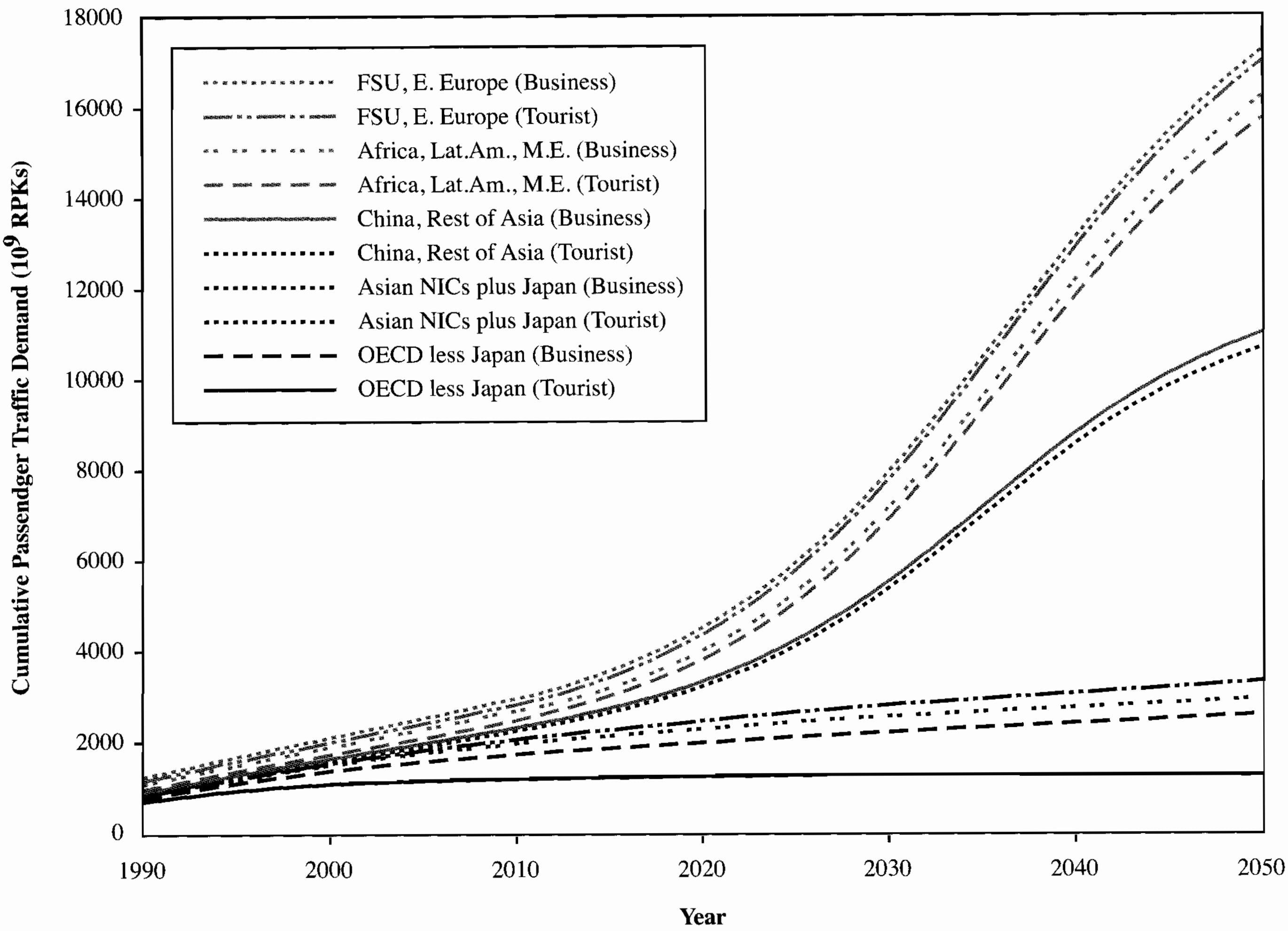


**Figure 9-29**: Distribution of passenger demand (IS92a scenario, Eab).

1990). This value contrasts with the 21% of total passenger demand projected for these two regions in the FESG model, based on the two regions' 33% share of GNP.

### *9.6.4. $NO_x$ Technology Projections*

A list of $NO_x$ emissions index projections is given in Table 9-23 for the three long-term models (IS92a scenarios).

The fleet EI($NO_x$) in 1992 was calculated as 12.0 (NASA), 13.8 (ANCAT/EC2), and 13.9 (DLR).

Expectations for the development of $NO_x$ technology are quite different among the models. The two FESG model $NO_x$ technology estimates were based on ICCAIA technology projections for new aircraft (Sutkus, 1997) and estimates of how quickly such new technology would enter the fleet (Greene and Meisenheimer, 1997). The assumptions in the DTI model were that regulatory pressures would require reductions in $NO_x$ emissions, and the fleet emissions index would be forced down as the engine industry responded with specific technology developments through 2035. These developments assumed the introduction of emission control technology that would produce engine emissions indices appropriate to those anticipated for staged combustor and ultra-low $NO_x$ combustor technology—the latter of the type being developed for HSCT applications [EI($NO_x$) =5]. Ultra-low $NO_x$ technology concepts now being developed may not be suitable for future high pressure ratio subsonic engine designs, so achieving fleet $NO_x$ emission levels assumed in the DTI and EDF models may be very difficult (see Section 7.5).

The EDF model used a logistic extrapolation of $NO_x$ trends from NASA work (Stolarski and Wesoky, 1993), but no changes in technology were explicitly specified.

***Table 9-23**: Comparison of fleet EI($NO_x$) from technology projections to 2050.*

| Scenario | Fleet EI($NO_x$) |
|---|---|
| Fa1 | 15.5 |
| Fa2 | 11.5 |
| DTI | 7.0 |
| Eab | 6.9 |

### 9.6.5. Infrastructure and Fuel Availability Assumptions

All of the long-term scenarios reviewed in this chapter were developed with the implicit assumption that sufficient system infrastructure and capacity will be available to handle the demand in an unconstrained fashion (infrastructure and capacity are defined for airports as runways, terminals, gates and aprons, roads, etc., and for airways as air navigation services, air traffic control, etc.). However, lack of infrastructure development may well impede future aviation growth. Lack of infrastructure will result in congestion and delay, additional fuel burn (in the air and on the ground), higher operating costs, higher ticket prices, and reduced service.

In some parts of the world, particularly in North America and Europe, the airway and airports system is currently operating under constraints that limit its ability to provide service. These constraints are likely to become more acute in the future as the demand for aviation services continues to grow. Congestion resulting from capacity constraints impairs the economic and environmental performance of airlines and the entire aviation system. To accommodate future demand, physical and technological infrastructure must be upgraded and expanded. In many areas, however, strong local pressures (especially related to noise created by aircraft movements) have constrained development of new airports and capacity improvements at existing airports. It is therefore important to note that the traffic forecasts reviewed in this chapter are all unconstrained forecasts that do not evaluate system capacity constraints when estimating future traffic growth.

Aviation also depends on petroleum fuels. For the past 50 years, known reserves of petroleum have continued to expand to satisfy 20–30 years of predicted demand. Over the short-term future, little change in the demand/supply situation is expected. Oil companies predict continued supply of their raw material, and kerosene supplies should have similar availability as the present day. Despite the forecast for increasing demand, oil prices are projected to rise only moderately over the next 20 years (Hutzler and Andersen, 1997). Over the period of these scenarios (to 2050), estimates of availability are less clear, but there is a general view that the oil industry will continue to meet demand (Rogner, 1997). There are, however, less optimistic views for oil production, with some predictions of a production decline occurring within the next decade (Campbell and Laherrere, 1998). The long-term scenarios assessed for this report implicitly assume continued availability of fuel at moderate prices. This is a key assumption for all scenarios because large increases in the price of fuel and/or shortages in supply would act to restrain demand for passenger and cargo air transport.

All of the scenarios ignore (in their baseline assumptions) possible changes in service patterns or infrastructure that a future HSCT might require. The effects of an HSCT fleet are considered in Section 9.5.

### 9.6.6. Plausibility Checks

Although none of the long-term scenarios reviewed here is considered impossible, some may be more plausible than others. We devised three simple checks to assess plausibility. The first estimated the fleet size required to carry projected traffic in 2050; the second examined implications for airport and infrastructure; and the third examined implications for kerosene demand. These plausibility checks represent an initial examination of the implications of the scenarios and are intended to illustrate possible consequences of traffic estimates resulting from the different scenarios. It must be emphasized that the fleet numbers produced by this analysis are approximate and are provided for comparative purposes only.

#### 9.6.6.1. Fleet Size

The fleet sizes implied by five of the scenarios were determined from the DTI traffic and fleet forecast model (see Section 9.3.2), which was developed primarily to project demand for new aircraft implied by 25-year traffic forecasts. The DTI model requires an annual traffic growth rate as an input; for this assessment purpose, this value was assumed to be a constant annual rate calculated from the base year traffic and the model's projection for 2050. The model assumes the fleet to comprise a range of jet aircraft types, described by seat capacity as follows: 80–99, 100–124, 125–159, 160–199, 200–249, 250–314, 315–399, 400–499, 500–624, and 625–799. The larger aircraft sizes have yet to be produced but are assumed to enter service beginning about 2005. Regional variations in fleet composition are reflected in the global fleet, based on current trends. This analysis does not capture the effects of compositional change that could be created as new markets develop. Average aircraft size growth is assumed (reflecting the historical trend of greater seating capacity for individual aircraft types over time). The future fleet required to satisfy the scenario demand estimates is derived through an iterative process by matching capacity to traffic demand, based on assumptions regarding aircraft unit productivity in capacity terms. Other model assumptions are as follows:

- Subsonic aircraft supply-projected demand (no supersonics)
- A short- and long-haul market share
- Future market functions as does the present day (i.e., no assumptions regarding wider deregulation are made)
- Unconstrained demand
- Aircraft retired at an average age of 25 years (reduced productivity from 20–30 years)
- Aircraft productivity to improve by an average of 0.75% annually.

The assumption regarding lack of constraints requires comment. Today's civil aviation market is constrained only by the practical limitations of airport capacity and access restrictions, airspace restrictions, and economic restraint resulting from taxation, charges, and so forth that affect ticket price. Any constraints in the future, whether to address environmental problems or as a the lowest growth case. Conversely, the highest growth case would require more than 1,300 new airports of 15 gates each (two new airports per month for 60 years) even if all 3,750 airports now listed in the OAG had 15 gates and were capable of handling large jet transport aircraft (which they do not and are not). This analysis ignores infrastructure location and the problems associated with its provision. In populous parts of the world, where civil aviation is established, the addition of airport capacity is often difficult given local environmental pressures such developments create. However, in developing countries, where much of the future traffic growth is anticipated, new infrastructure might encounter less environmental sensitivity and therefore be more readily provided. Nonetheless, the infrastructure projects required to satisfy the highest growth scenarios are unprecedented in scope.

### 9.6.6.3. *Fuel Availability*

All of the 2050 scenarios imply large increases in fuel consumption by aircraft. In the highest FESG scenario (Fe2), aircraft fuel consumption increases from 139 to 772 Tg $yr^{-1}$ over the period 1992 to 2050. In the highest EDF scenario (Eeh), the increase is from 179 Tg $yr^{-1}$ in 1990 to 2,297 Tg $yr^{-1}$ in 2050. Because both scenarios are based on the IS92e scenario, it is appropriate to compare these figures to total energy use in the IS92e scenario. According to scenario Fe2, aircraft will account for 13% of the total transportation energy usage in 2050 and require 15% of the world's liquid fossil fuel production. The EDF scenario (Eeh) implies that aircraft account for 39% of the transportation energy usage and require 45% of the world's liquid fuel production. These comparisons assume that aircraft do not use biomass fuels or fuels derived from natural gas.

Under either scenario, the world will be straining the limits of conventional oil resources by 2050. Total remaining resources of conventional petroleum, discovered and undiscovered, have been estimated at between one trillion (Campbell and Laherrere, 1998) and two trillion barrels (Masters *et al.*, 1994—based on the optimistic 5% probability estimate of undiscovered oil). The IS92e scenario implies cumulative production of liquid fuels of 1 trillion barrels by 2025 and 2 trillion barrels by 2050. Cumulative consumption by 2050 by aircraft alone amounts to 0.15 trillion barrels in the Fe2 scenario and 0.35 trillion barrels in the Eeh scenario. However, production of liquid fuels is not necessarily limited by conventional oil resources. Liquid fuels can be produced from heavy oil, tar sands, oil shale, or even coal, albeit with significantly greater environmental consequences and at higher costs. High fuel prices would violate the explicit assumptions used in developing the scenarios.

### 9.6.6.4. *Manufacturing Capability and Trends in Aircraft Capacity*

In 1997, the global aircraft manufacturing capability delivered 634 passenger jet aircraft, bringing the global jet passenger fleet to approximately 10,000 aircraft. The rate of new aircraft deliveries has followed a generally increasing trend since the mid-1950s, and this trend must continue over the scenario period to satisfy predicted demand for new and replacement aircraft. For the demand cases examined above, deliveries of new aircraft are estimated to reflect the schedule given in Table 9-27.

***Table 9-27****: Required yearly delivery rates of aircraft implied by scenarios.*

| | **Total Aircraft Deliveries (in these years)** | | | |
|---|---|---|---|---|
| **Year** | Eab | Eeh | Fa1,2 | DTI |
| 2020 | 1,106 | 1,667 | 813 | 1,012 |
| 2030 | 1,072 | 1,933 | 686 | 945 |
| 2040 | 1,566 | 3,058 | 931 | 1,354 |
| 2050 | 1,714 | 3,831 | 948 | 1,440 |

The delivery rate for the Fa1 and Fa2 scenarios would be achievable with existing manufacturing capacity. The delivery rate required by the highest scenario, Eeh, implies a considerable increase in manufacturing capacity—approximately six times that existing today. Although this level is not impossible, such an expansion of aircraft manufacturing capability is likely to be difficult to achieve and sustain during the period. The Eab scenario implies a delivery rate that is approximately three times the level existing today, which is not implausible for 2050.

One assumption intrinsic to the fleet size analysis was that the average number of seats per aircraft will increase by 1% each year, reflecting current trends. This assumption has a large effect on fleet size estimates, particularly for high-demand cases. As a sensitivity analysis, the factor was changed to 2% per year for the Eeh high scenario and for the Fa1 and Fa2 scenarios. Such a change may reflect potential market pressures for larger aircraft, which is not inappropriate for a high traffic growth scenario. The results are given in Table 9-28.

As this analysis shows, a different assumption in aircraft size growth has a significant effect on the estimated future fleet. The projected numbers of the largest aircraft types (between 625 and 799 seats) in future fleets are particularly sensitive in this analysis, which suggests that there might be more than 7,000 such aircraft in the fleet by 2050 in the Eeh scenario (compared with about 10,000 passenger aircraft of all sizes today) or about 4,000 additional aircraft for the more conservative Fa1 and Fa2 scenarios.

Increased capacity can be supplied by additional aircraft, increased flying hours (i.e., more efficient use of the fleet),

***Table 9-28****: Sensitivity of fleet size to aircraft capacity.*

| **Aircraft Size Growth Assumption** | **Fleet at 2050 – Total Aircraft** 1% $yr^{-1}$ | 2% $yr^{-1}$ |
|---|---|---|
| Eeh scenario | 69,275 | 42,448 |
| Fa1,2 scenario | 21,209 | 11,913 |

***Table 9-29**: Summary data from long-term scenarios.*

| Scenario Year | Scenario Name | Traffic Demand ($10^9$ RPK) | Calculated Fuel Burned (Tg $yr^{-1}$) | Calculated $CO_2$ (as C) (Tg $yr^{-1}$) | Calculated $NO_x$ (as $NO_2$) (Tg $yr^{-1}$) | Calculated Fleet EI($NO_x$) (g $NO_2$/kg fuel) |
|---|---|---|---|---|---|---|
| 2041 | WWF | n/a | 639.5[a] | 550.0 | n/a | n/a |
| 2050 | Fa1 | 13,934 | 471.0 | 405.1 | 7.2 | 15.2 |
| 2050 | Fa1H | 13,934 | 557.0 | 479.0 | 7.0 | 12.6 |
| 2050 | Fa2 | 13,934 | 487.6 | 419.4 | 5.5 | 11.4 |
| 2050 | Fc1 | 7,817 | 268.2 | 230.6 | 4.0 | 15.0 |
| 2050 | Fc2 | 7,817 | 277.2 | 238.4 | 3.1 | 11.3 |
| 2050 | Fe1 | 21,978 | 744.3 | 640.1 | 11.4 | 15.3 |
| 2050 | Fe1H | 21,978 | 831.0 | 714.7 | 11.3 | 13.6 |
| 2050 | Fe2 | 21,978 | 772.1 | 664.0 | 8.8 | 11.4 |
| 2050 | Eab | 23,257 | 1,143.0 | 983.0 | 7.9 | 6.9 |
| 2050 | Eah | 41,392 | 2,086.0 | 1,794.0 | 14.4 | 6.9 |
| 2050 | Ecb | 16,762 | 837.0 | 720.0 | 5.8 | 6.9 |
| 2050 | Ech | 29,934 | 1,528.0 | 1,314.1 | 10.5 | 6.9 |
| 2050 | Edb | 19,555 | 959.0 | 824.8 | 6.6 | 6.9 |
| 2050 | Edh | 33,655 | 1,689.4 | 1,452.8 | 11.6 | 6.9 |
| 2050 | Eeb | 26,886 | 1,298.0 | 1,116.3 | 9.0 | 6.9 |
| 2050 | Eeh | 46,363 | 2,297.0 | 1,975.4 | 15.8 | 6.9 |
| 2050 | DTI | 18,106 | 633.2 | 544.6 | 4.5 | 7.0 |
| 2050 | MIT | n/a[b] | 977.0[a] | 840.0[b] | n/a | n/a |

[a]Fuel burned calculated from published $CO_2$ data.
[b]Contains unspecified fraction from high-speed rail.

larger aircraft, or a combination of these factors. The high aircraft growth assumption used as a sensitivity analysis here suggests that about 70% of future capacity growth will be supplied by an increase in aircraft size. Although such an industry trend is not impossible, it is unlikely to occur in such a prescriptive manner if the industry remains relatively deregulated. Deregulation tends to favor increased frequency and direct flights with smaller aircraft between departure and destination. However, it is likely that some markets would favor the proliferation of very large aircraft, especially those with dense traffic flows. The size of the fleets suggested by the 2% per year aircraft size growth assumption must therefore be regarded as toward the low end of the range.

#### 9.6.6.5. *Synthesis of Plausibility Analyses*

Given the range of estimates for traffic, fuel consumption, and emissions from the 2050 aircraft scenarios available to this assessment, it is necessary to comment on the plausibility of the results—not least to demonstrate that results used in subsequent analyses are bounded by sensible limits within which the aviation industry is currently envisaged to develop.

The foregoing analyses suggest that although none of the scenarios considered for 2050 is impossible, some of the high-growth scenarios (e.g., Eah and Eeh) are probably less plausible. The fleet size and infrastructure implications suggest radical developments that are likely to be beyond the scope of changes observed in the industry thus far (or anticipated for the future). Similarly, the low-growth scenarios—though plausible in terms of achievability—give traffic estimates that are likely to be exceeded given the present state of the industry and planned developments. Although all of the FESG scenarios discount the possibility of truly radical developments in technology over the next 50 years, they are considered to fall within a plausible range of outcomes and suggest achievable developments for the industry.

The 3-D gridded output from scenarios Fa–Fe (with T1 and T2 technology scenarios) and from DTI are suitable for use as input to chemical transport models and may be used to calculate the effect of aviation $CO_2$ emissions. Scenarios Eab and Edh are suitable for use in Chapter 6 to calculate the effect of $CO_2$ emissions as sensitivity analyses because the latter scenario projects $CO_2$ emissions levels from aviation that are 2.2 times greater in 2050 than the highest of the FESG scenarios. Table 9-29 provides a summary of all of the long-term scenarios examined in the chapter.

## References

**ANCAT/EC,** 1995: *A Global Inventory of Aircraft $NO_x$ Emissions*. A first version (April 1994) prepared for the AERONOX programme. Abatement of Nuisances Caused by Air Transport (ANCAT) and European Community Working Group, European Civil Aviation Conference, London, United Kingdom, 20 pp.

**Albritton,** D.L, G.T. Amanatidis, G. Angeletti, J. Crayston, D.H. Lister, M. McFarland, J.M. Miller, A.R. Ravishankara, N. Sabogal, N. Sundararaman, and H.L. Wesoky, 1997: *Global Atmospheric Effects of Aviation: Report of the Proceedings of the Symposium.* NASA-CP-3351, National Aeronautics and Space Administration, Washington, DC, USA, 52 pp.

**Atkinson,** A.B., 1975: *The Economics of Inequality.* Clarendon Press, Oxford, United Kingdom, pp. 22, 246.

**Balashov,** B. and A. Smith, 1992: ICAO analyses—trends in fuel consumption by world's airlines. *ICAO Journal,* **47(8),** 18–21.

**Barrett,** M., 1994: *Pollution Control Strategies for Aircraft.* World Wide Fund for Nature, Gland, Switzerland, 60 pp.

**Bauer,** E., 1979: A catalog of perturbing influences on stratospheric ozone, 1955–1975. *Journal of Geophysical Research,* **84,** 6929–6940.

**Baughcum,** S.L., S.C. Henderson, P.S. Hertel, D.R. Maggiora, and C.A. Oncina, 1994: *Stratospheric Emissions Effects Database Development.* NASA-CR-4592, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 156 pp.

**Baughcum,** S.L., and S.C. Henderson, 1995: *Aircraft Emission Inventories Projected in Year 2015 for a High Speed Civil Transport (HSCT) Universal Airline Network.* NASA-CR-4659, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 117 pp.

**Baughcum,** S.L., S.C. Henderson, and T.G. Tritz, 1996a: *Scheduled Civil Aircraft Emission Inventories for 1976 and 1984: Database Development and Analysis.* NASA-CR-4722, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 144 pp.

**Baughcum,** S.L., S.C. Henderson, T.G. Tritz, and D.C. Pickett, 1996b: *Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis.* NASA-CR-4700, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 196 pp.

**Baughcum,** S.L., D.J. Sutkus, Jr., and S.C. Henderson, 1998: *Year 2015 Aircraft Emission Scenario for Scheduled Air Traffic.* NASA-CR-1998-207638, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 44 pp.

**Baughcum,** S.L., and S.C. Henderson, 1998: *Aircraft Emission Scenarios Projected in Year 2015 for the NASA Technology Concept Aircraft (TCA) High Speed Civil Transport.* NASA CR-1998-207635, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 31 pp.

**Beck,** J.P., C.E. Reeves, F.A.A.M. de Leeuw, and S.A. Penkett, 1992: The effect of aircraft emissions on tropospheric ozone in the Northern Hemisphere. *Atmospheric Environment,* **26A,** 17–29.

**Boeing Commercial Airplane Group,** 1993: *1993 Current Market Outlook* [Sepanen, D. (ed.)]. Boeing Commercial Airplane Group, Seattle, WA, USA, March 1993, 58 pp.

**Boeing Commercial Airplane Group,** 1996: *1996 Current Market Outlook* [Meskill, T. (ed.)]. Boeing Commercial Airplane Group, Seattle, WA, USA, March 1996, 38 pp.

**Boeing Commercial Airplane Group,** 1998: *1998 Current Market Outlook* [Meskill, T. (ed.)]. Boeing Commercial Airplane Group, Seattle, WA, USA, March 1998, 60 pp.

**Brasseur,** G.P., R.A. Cox, D. Hauglustaine, I. Isaksen, J. Lelieveld, D.H. Lister, R. Sausen, U. Schumann, A. Wahner, and P. Wiesen, 1998: European scientific assessment of the atmospheric effects of aircraft emissions. *Atmospheric Environment,* **32,** 2329–2418.

**CAEP/4-FESG,** 1998: *Report 4. Report of the Forecasting and Economic Analysis Sub-Group (FESG): Long-Range Scenarios.* International Civil Aviation Organization Committee on Aviation Environmental Protection Steering Group Meeting, Canberra, Australia, January 1998, 131 pp.

**CAEP/WG3,** 1995: *Report of the Emissions Inventory Sub-group.* International Civil Aviation Organization Committee on Aviation Environmental Protection Working Group 3 [Ralph, M. (ed.)], London, United Kingdom, 45 pp.

**Campbell-Hill Aviation Group,** 1998: *Airport and Infrastructure Implications,* private communication, Brian M. Campbell to Anu Vedantham, December 1998.

**Campbell,** C.J. and J.H. Laherrere, 1998: The end of cheap oil. *Scientific American,* **278(3).**

**COMESA,** 1975: *Report of the Committee on Meteorological Effects of Stratospheric Aircraft.* UK Department of Defence, Bracknell, Berks, United Kingdom

**Deidewig,** F., A. Döpelheuer, and M. Lecht, 1996: *Methods to Assess Aircraft Engine Emissions in Flight.* Proceedings of the 20th International Council of Aeronautical Sciences Congress, Sorrento, Italy, Sept. 1996. American Institute of Aeronautics and Astronautics, Reston, Virginia, USA, Vol. I, pp 131–141.

**Derwent,** R.G., 1982: Two-dimensional model studies of the impact of aircraft exhaust emissions on tropospheric ozone. *Atmospheric Environment,* **16,** 1997–2007.

**Friedl,** R.R. (ed.), 1997: *Atmospheric Effect of Subsonic Aircraft: Interim Assessment Report of the Advanced Subsonic Technology Program.* NASA Reference Publication 1400, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD, USA, 154 pp.

**Gardner,** R.M., K. Adams, T. Cook, F. Deidewig, S. Ernedal, R. Falk, E. Fleuti, E. Herms, C.E. Johnson, M. Lecht, D.S. Lee, M. Leech, D. Lister, B. Masse, M. Metcalfe, P. Newton, A. Schmitt, C. Vandenbergh, and R. Van Drimmelen, 1997: The ANCAT/EC global inventory of $NO_x$ emissions from aircraft. *Atmospheric Environment,* **31(12),** 1751 and 1766.

**Gardner,** R.M. (ed.), 1998: *ANCAT/EC2 Global Aircraft Emissions Inventories for 1991/1992 and 2015: Final Report.* EUR-18179, ANCAT/EC Working Group, ISBN-92-828-2914-6, 84 pp. + appendices.

**Greene,** D.L., 1992: Energy-efficiency improvement potential of commercial aircraft. In: *Annual Review of Energy and the Environment* [Hollander, J., J. Harte, and R. H. Socolow (eds.)]. Annual Reviews, Inc., Palo Alto, CA, USA, Vol. 17, pp. 537–574.

**Greene,** D.L. and L. Meisenheimer, 1997: *Commercial Air Transport Emission Scenario Model.* Oak Ridge National Laboratory Center for Transportation Analysis, Oak Ridge, TN, USA, October 6, 1997, 6 pp.

**Gould,** R., 1996: *Environmental Management for Airports and Aviation: Jane's Special Report.* Jane's Information Group, Surrey, United Kingdom, January 1996, 253 pp.

**Hidalgo,** H. and P.J. Crutzen, 1977: The tropospheric and stratospheric composition perturbed by $NO_x$ emissions of high-altitude aircraft. *Journal of Geophysical Research,* **82,** 5833–5866.

**Hutzler,** M.J. and A.T. Andersen, 1997: *International Energy Outlook 1997.* Energy Information Agency, Washington, DC, USA.

**ICAO,** 1993: *Environmental Protection: Annex 16 to the Convention on International Civil Aviation – Volume II, Aircraft Engine Emissions.* International Civil Aviation Organization, Montreal, Quebec, Canada, 63 pp.

**ICAO,** 1995: *ICAO Engine Exhaust Emissions Databank, 1st Edition—1995.* ICAO-9646-AN/943, International Civil Aviation Organization, Montreal, Quebec, Canada, 173 pp.

**ICAO,** 1997a: *Outlook for Air Transport to the Year 2005.* ICAO Circular 270-AT/111, International Civil Aviation Organization, Montreal, Quebec, Canada, 53 pp.

**ICAO,** 1997b: *Traffic: Commercial Air Carriers 1982–96, Digest of Statistics No. 337.* International Civil Aviation Organization, Montreal, Quebec, Canada, 353 pp.

**Landau,** Z.H., M. Metwally, R. Van Alstyne, and C.A. Ward, 1994: *Jet Aircraft Engine Exhaust Emissions Database Development—Year 1990 and 2015 Scenarios.* NASA-CR-4613, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 88 pp.

**Leggett,** J., W.J. Pepper, and R.J. Swart, 1992: Emissions scenarios for the IPCC: an update. In: *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Prepared by IPCC Working Group I [Houghton, J.T., B.A. Callander, and S.K. Varney (eds.)] and WMO/UNEP. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 68–95.

**Little,** A.D., 1975: *Preliminary Economic Impact Assessment of Possible Regulatory Action to Control Atmospheric Emission of Selected Halocarbons.* Report C77327-10, U.S. Environmental Protection Agency, Menlo Park, CA, USA.

**McInnes,** G. and C.T. Walker, 1992: *The Global Distribution of Aircraft Air Pollutant Emissions.* Warren Spring Laboratory Report LR 872, Department of Trade and Industry, Warren Spring Laboratory, Stevenage, Hertfordshire, United Kingdom, 41 pp.

**Metwally,** M., 1995: *Jet Aircraft Engine Emissions Database Development—1992 Military, Charter, and Nonscheduled Traffic*. NASA-CR-4684, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 61 pp.

**Mortlock,** A.M. and R. van Alstyne, 1998: *Military, Charter, Unreported Domestic Traffic and General Aviation: 1976, 1984, 1992, and 2015 Emission Scenarios*. NASA-CR-1998-207639, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 118 pp.

**Newton,** P.J. and R.S. Falk, 1997: *DTI Forecast of Fuel Consumption and Emissions from Civil Aircraft in 2050 Based on ANCAT/EC2 1992 Data*. DTI/ADI3c/199701/1.0, Department of Trade and Industry, London, United Kingdom, 13 November 1997, 15 pp.

**Nüßer,** H.-G. and A. Schmitt, 1990: The global distribution of air traffic at high altitudes, related fuel consumption and trends. In: *Air Traffic and the Environment, Lecture Notes in Engineering* [Schumann, U. (ed.)]. Springer-Verlag, Berlin, Germany, pp. 1–11.

**OECD,** 1998a: *Energy Balances of OECD Countries* (database software). Organization for Economic Cooperation and Development, OECD Publications, Paris, France.

**OECD,** 1998b: *Energy Balances of Non-OECD Countries* (database software). Organization for Economic Cooperation and Development, OECD Publications, Paris, France.

**Olivier,** J.G.J., 1995: *Scenarios for Global Emissions from Air Traffic. The Development of Regional and Gridded (5° x 5°) Emissions Scenarios for Aircraft and for Surface Sources, Based on CPB Scenarios and Existing Emission Inventories for Aircraft and Surface Sources*. RIVM-773002003, Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven, The Netherlands, July 1995, 113 pp.

**Pulles,** H., 1998: *Report of the (ICAO/CAEP) Focal Point on Charges (FPC) Prepared for CAEP/4. Emission Charges and Taxes in Aviation*. International Civil Aviation Organization Committee on Aviation Environmental Protection, The Hague, The Netherlands, March 1998, 79 pp. + appendices.

**Rogner,** H.H., 1997: An assessment of world hydrocarbon resources. In: *The Annual Review of Energy and the Environment*. Annual Reviews, Inc., Palo Alto, CA, USA, Vol. 22, pp. 217–262.

**Schafer,** A. and D.G. Victor, 1997: *The Future Mobility of the World Population*. Discussion Paper 97-6-4, Center for Technology, Policy and Industrial Development and the MIT Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, USA, Rev. 2, September 1997, 39 pp.

**Schmitt,** A. and B. Brunner, 1997: Emissions from aviation and their development over time. In: *Final Report on the BMBF Verbundprogramm, Schadstoffe in der Luftfahrt* [Schumann, U., A. Chlond, A. Ebel, B. Kärcher, H. Pak, H. Schlager, A. Schmitt, and P. Wendling (eds.)]. DLR-Mitteilung 97-04, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen and Cologne, Germany, pp. 37–52.

**Schulte,** P., H. Schlager, H. Ziereis, U. Schumann, S.L. Baughcum, and F. Deidewig, 1997: NOx emission indices of subsonic long-range jet aircraft at cruise altitude: *In situ* measurements and predictions. *Journal of Geophysical Research,* **102,** 21431–21442.

**Stolarski,** R., and H. Wesoky, 1993: *The Atmospheric Effects of Stratospheric Aircraft: A Third Program Report*. NASA Reference Publication 1313, National Aeronautics and Space Administration, Washington, DC, USA, November 1993, 422 pp.

**Sutkus,** D.J., Jr., 1997: *2050 Fuel Efficiency and $NO_x$ Technology Scenarios*. International Coordinating Council of Aerospace Industries Association Working Paper WG3-WP4/22 presented at the Fourth Meeting of International Civil Aviation Organization Committee on Aviation Environmental Protection Working Group 3 (Emissions), 12–14 November 1997, Bern, Switzerland, 22 pp.

**Sutkus,** D.J. Jr., D.L. Daggett, D.P. DuBois, and S.L. Baughcum, 1999: *An Evaluation of Aircraft Emissions Inventory Methodology by Comparisons with Reported Airline Data*. National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, (in press).

**ten Have,** H.B.G. and T.D. de Witte, 1997: *User Manual of the Flights and Emissions Model—Model Version 3.11*. NLR-CR 97063-L, National Aerospace Laboratory, Amsterdam, The Netherlands.

**Vedantham,** A. and M. Oppenheimer, 1994: *Aircraft Emissions and the Global Atmosphere*. Environmental Defense Fund, New York, NY, USA, 77 pp.

**Vedantham,** A. and M. Oppenheimer, 1998: Long-term scenarios for aviation: demand and emissions of $CO_2$ and $NO_x$. *Energy Policy,* **26(8),** 625–641.

**WMO,** 1995: *Scientific Assessment of Ozone Depletion: 1994*. Report no. 37, Global Ozone Research and Monitoring Project, World Meteorological Organization, Geneva, Switzerland, 578 pp.

**Wuebbles,** D.J., D. Maiden, R.K. Seals, S.L. Baughcum, M. Metwally, and A. Mortlock, 1993: Emissions scenarios development: report of the emissions scenarios committee. In: *The Atmospheric Effects of Stratospheric Aircraft: A Third Program Report* [Stolarski, R.S. and H.L. Wesoky (eds.)]. NASA Reference Publication 1313, National Aeronautics and Space Administration, Washington, DC, USA, pp. 63–85.

**Zahavi,** Y., 1981: *The UMOT-Urban Interactions*. DOT-RSPA-DPB 10/7, U.S. Department of Transportation, Washington, DC, USA, 151 pp.